Technical Assessment for Building Automation Systems

Sector: Buildings

Agency Level: Building And Facility Owners

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Acronyms and Symbols Used

- ***AFDD*** – Automatic Fault Detection and Diagnosis
- ***BACS*** – Building Automation and Control System
- ***BAS*** – Building Automation Systems
- ***BEMS*** – Building Energy Management System
- ***BMS*** – Building Management System
- ***DCV*** – Demand Controlled Ventilation
- ***DDC*** – Direct Digital Controls
- ***EICS*** – Energy Integrated Control Systems
- ***EMCS*** – Energy Management Control System
- ***EMIS*** – Energy Management and Information System
- ***HEM*** – Home Energy Management
- ***HVAC*** – Heating, Ventilation and Air-Conditioning
- ***IAQ*** – Internal Air Quality
- ***IoT*** – Internet of Things
- ***NZEB*** – Net Zero Energy Building
- ***OA*** – Outdoor Air
- ***OBC*** – Occupancy-based Control
- ***PDS*** – Project Drawdown Scenario
- ***PEB*** – Positive Energy Building
- ***PNNL*** – Pacific Northwest National Laboratories
- ***REF*** – Reference (Scenario)
- ***RTU*** – Rooftop Units
- ***SB*** – Smart Building
- ***SEB*** – Smart Energy Building
- ***TAM*** – Total Addressable Market
- ***TBM*** – Technical Building Management
- ***WGBC*** – World Green Building Council

EXECUTIVE SUMMARY

Globally, the buildings sector is the largest end-use sector, accounting for over 40% of global energy usage and as much as 33% of global CO_2e emissions in both developed and developing countries (Peng, 2016) p.453. Thus, the global building sector needs innovative technologies and approaches to reduce energy consumption while ensuring building operations are not affected. A technology that has historically been common in large, commercial buildings that can reduce energy consumption is a building automation and controls system (BAS). These systems function as the brain of a commercial building and are responsible for sensing and controlling any number of building functions and facilities ranging from heating, ventilation, and air conditioning to lighting and refrigeration. In recent years, advanced BAS systems have evolved to become the core technology of a new generation of buildings largely known as Smart Energy Buildings (SEB): buildings equipped to respond to real-time market, weather and occupant conditions using the latest information and communications technologies (ICT) on the market (Rocha, Siddiqui, & Stadler, 2015).

Increased development of SEBs has increased excitement around the future of advanced BAS technologies, but this is an area within energy and building efficiency that remains historically under-studied. The benefits for large and, increasingly, for small- and medium-sized buildings are significant as they can enhance occupant satisfaction and reduce the total cost of ownership (TCO) by saving energy. Whereas an upgrade to an isolated system can result in energy savings of 5–15%, an advanced BAS can realize 30–50% savings in existing buildings that are otherwise inefficient.

There are barriers to implementation in smaller buildings and those outside of the US and EU; barriers include the high upfront costs of BAS, functionality gaps, and lack of standardization in the field. But trends in automation and the growing advance of the Internet of Things (IoT) and connected, communicating devices can accelerate adoption of BAS across the global commercial building stock.

A model was developed to show the impact of such adoption by constructing two types of scenarios for future BAS growth. Project Drawdown Scenarios (PDS) were built upon recent initiatives that advocate for reducing all emissions from the global building sector and projects rapid adoption for BAS in commercial buildings. The reference scenario (REF) fixes future growth of this solution to its current percentage of the total addressable market in each region, calculated in the model's base year as 57 percent. Comparing each PDS with the REF allows modeling of the climate and financial impacts of PDS adoption. An aggressive PDS scenario that aligns the building sector with a global goal of achieving drawdown by 2050 forecasts that over 69 billion m^2 of commercial floor space will be integrated into an advanced BAS by 2050.

The climate and financial benefits of this rapid adoption for BAS in commercial buildings is substantial. PDS adoption avoids over 6 gigatons of CO_2-equivalent greenhouse gas emissions or 0.82 ppm. In addition, the costs of implementing BAS across the commercial building stock are not overly burdensome, as they only require a marginal investment of $238 billion in the PDS compared to the REF scenario. The PDS scenario, however, saves over $2,699 billion in operating savings due to the reductions in energy expenditures in commercial buildings over the lifetime of installed systems. These results suggest that this solution can play a significant role in reducing carbon emissions while yielding massive savings for building owners.

1 Literature Review

Globally, the buildings sector is one of the largest end-use sectors, accounting for 30% of global final energy usage. Including building construction increases this to 36%. These two together 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 lie. 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.

In the last five years, the term "Smart", as used in "Smart Cities", "Smart Grids", and "Smart buildings", has been used to define solutions that reach beyond the idea of simply 'automation'. The terms "Smart Energy" or "Smart Energy Systems" represents a broader view of building energy and strategies for its optimal use (Lund et al. 2017). Smart cities have the potential to make a major contribution to the reduction of the impacts of climate change (Norman 2018). Areas of impact include not only mobility, buildings, and energy, but also water and governance. The next evolution of the smart city is the application of its concepts to the confined physical space of commercial building environments (Minoli et al. 2017).

Smart Buildings (SB): Also commonly known as "intelligent buildings", can be thought of as an ensemble of systems that integrate: information and communications technologies (ICT), human feedback and preferences, and the building's physical infrastructure systems (Abrol, Mehmani, Kerman, Meinrenken, & Culligan, 2018). SB prepare building managers to respond to real-time market and weather conditions by taking advantage of advances in ICT (Rocha et al., 2015, p. 203) with the purpose of optimizing buildings for all their varied end uses.

Smart Energy Buildings (SEB): These buildings include an advanced, high-performance building automation systems and Control System (BAS) coupled with technical building management (TBM) to dramatically reduce building energy consumption while improving building operations and the indoor environment (Roth, Westphalen, Feng, Llana, & Quartararo, 2005). They use a range of sensors throughout the building to measure temperature, CO_2, airflow, occupancy, and daylight levels, and they integrate these sensors with a central system connected to an array of actuators that control the functioning of individual building systems.

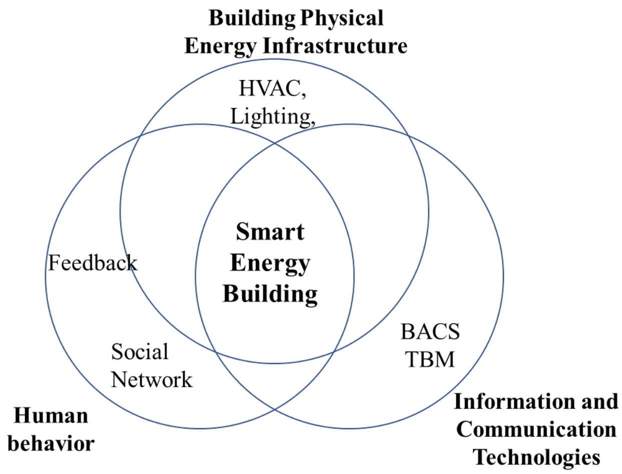

Figure 1.1 Components of Smart Energy Buildings, Source: Abrol et al. 2018

Buildings are complex systems and they involve a large number of individual components, each with highly technical systems and operating procedures. There are a number of terms that are frequently used when discussing building automation. The literature demonstrates little consensus on these definitions between energy authorities, academia, and industry groups. However, in staying consistent with the EN 15232:2017 standard, this report uses the term building automation and control systems (BAS) and technical building management (TBM).

- ***Building Automation Control Systems (BAS)***
  A Building Automation System (BAS) automates "tasks in technologically-enabled environments, coordinating a number of electrical and mechanical devices interconnected in a distributed manner by means of underlying control networks" (Domingues, Carreira, Vieira, & Kastner, 2016). BAS is also defined as "a system that is designed to control building operations and indoor climate, and to monitor and report system failures" (Granderson et al., 2011, p. iii). BAS "refers to those centralized and automated systems that can save energy within commercial buildings" (IEA, 2013, p. 194). BAS are also presented in the literature as building automation technologies (BAT), building control systems (BCS), building management systems (BMS), and building automation and control systems (BACS) (Shaikh, Nor, Nallagownden, Elamvazuthi, & Ibrahim, 2014) (p.420). In this report, all of these terms are used as synonyms of BAS. For instance, the ISO standards use the term BAS (ISO, 2004) as well as the energy agencies (IEA, 2013; U.S. EIA, 2012); however, in recent years the term Building Automation and Control Systems (BACS) has been massified through the adoption in the European standard "EN 15232-1:2017 Energy Performance of Buildings. Impact of Building Automation, Controls and Building Management" (CEN, 2017, p. 2017) and the increasing literature on this topic.

  BAS are defined as "*comprising all products and engineering services for automatic controls (including interlocks), monitoring, optimization, for operation, human intervention and management to achieve energy–efficient, economical and safe operation of building services*"

(Tichelen, Verbeke, & Waide, 2018); "*a comprehensive platform that is employed to monitor and control a building's mechanical and electrical equipment; used to manage loads and enhance efficiency, thus having the ability to reduce the energy needed to illuminate, heat, cool and ventilate a building*" (Minoli et al. 2017).

In this report, the term BAS refers to the automation of systems used in monitoring and controlling facilities that consume energy. "BAS" and "Building Automation Systems" refer to the most advanced versions of BAS, while conventional building use standard BAS versions that rely on manual switches and basic thermostats.

- ***Technical Building Management (TBM)***
  Technical Building Management (TBM), also known as Building Energy Management Systems (BEMS), Energy Management and Information Systems (EMIS); or Energy Integrated Control Systems (EICS), is a subset of Building Management Systems (BMS) and is a critical component of BAS. TBM, or an Energy Management and Information System, is the broad and rapidly evolving family of tools for monitoring, analyzing, and controlling building energy use and system performance (USDOE, 2018). TBM provides information for operating, maintaining, and managing buildings especially for energy management - Trending and alarming capabilities and detection of unnecessary energy use (Siemens BT, 2009). TBM is often used synonymously with BEMS, EMIS or EICS. When any of these terms is used, they imply the integrated control of a system rather than individual equipment-level control.

The advanced BAS and TBM can be thought of as the "brain" of a commercial building that is responsible for sensing, monitoring, and controlling the different functions of a building's facilities. While many large commercial buildings have a BMS to manage basic system functions, these systems often do not integrate various building systems into one with networked automation and control (as shown in Table 1.1).

Table 1.1 Advanced Building Automation Systems compared to Conventional Building Systems

Advanced BAS	Conventional Building Systems
Centralized, integrated, and networked Approach	Centralized approach
Intelligent Controls: (i) Learning based methods including artificial intelligence, fuzzy systems and neural networks; (ii) model based predictive control techniques; and (iii) agent based control systems. (Shaikh et al. 2014) p.421.	Conventional Controls: standard control systems, including on/off switching controllers, thermostats, proportional–integral and proportional–integral–derivative controllers
Respond to outside conditions (Rocha et al. 2015)	Proportional–integral and proportional–integral–derivative controllers are closed loop/feedback controls. They use static set-point temperatures for heating and cooling and sometimes disregard external conditions (Rocha et al. 2015)

Advanced BAS	Conventional Building Systems
DDC	Pneumatic and Electronic controls

Source: Rocha et al. 2015, Shaikh et al. 2014

Importantly, there are many facility-specific sensor and control technologies that can increase the energy performance of individual systems, and deploying these sensory technologies, such as Demand-Controlled Ventilation or Photosensor-based Lighting Control, can improve the energy performance of commercial buildings.

For the purposes of this report, however, advanced BAS is the focus rather than system-specific technologies. This is for several reasons. Firstly, the energy savings potential of different approaches specific to individual systems are not always additive because energy savings resulting from one approach in some cases might preclude savings from another approach (Roth et al, 2005). Secondly, approaches to automating individual systems are not always appropriate for all commercial buildings. For instance, in office buildings that have very predictable occupancy patterns, occupancy-based lighting controls may yield significant savings, but the same savings may not result in buildings such as hospitals that have more constant occupancy levels.

Because the model is not constructed at the individual building level but rather considers all types of commercial buildings across different world regions, it is not practical to use an individual system-level approach for calculating energy savings for BAS. In addition, integrated systems for energy management and building automation have demonstrated considerable potential for reducing consumption across the entire building environment, and there exist many opportunities for both new construction of buildings with these systems as well as opportunities to retrofit existing buildings with a BAS (BSRIA, 2014).

There are, of course, limitations to this approach, and these will be explained in greater detail in the Methodology Section. It is useful to keep in mind that a central BAS may have significantly different savings potentials in different types of commercial buildings and in different world regions. Moreover, given the sparseness of literature relevant to this topic, this report draws primarily on several comprehensive reports[1] of buildings controls and diagnostic approaches.

This section begins with an overview of advanced BAS technology, including an explanation of the functions of different sensor and controls involved in BAS. Next, it reviews BAS communication protocols and then discusses several applications of BAS to individual building systems, including HVAC, lighting, and other power systems. The section continues with a summary of the current market for BAS and the possible adoption paths and a discussion of market drivers and barriers for implementation of this technology globally. It concludes by assessing some of the advantages and disadvantages of BAS adoption.

1.1 BAS Technology Overview

There are several core technological components that comprise the BAS technology in the context of BAS. For the purpose of this study, the description provided by Lilis et al, 2016 is used. In this approach, three

[1] These include: Roth et al, 2005; Brambley et al., 2005; and Siemens 2009.

hierarchical levels of functionality organize the BAS: the top level, called the "management level" is where all the information from the system is collected, aggregated and represented to the operators; the middle level or "automation level" includes all the infrastructure capable of applying a predefined scenario maintaining a control set point; finally, the bottom level, or "field level" includes all the end-devices and field buses which interface with the physical world .

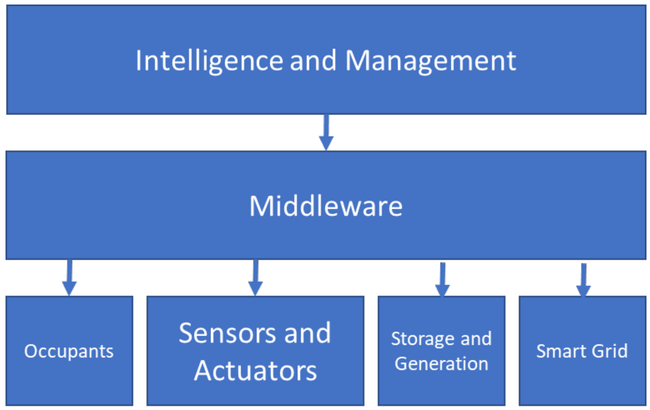

Figure 1.2. Layered approach of a typical BAS based on Lilis et al. 2016

BAS cover a broad range of many different software and hardware types. At the field level, sensors measure parameters such as temperature, humidity, daylight, and occupancy, while controllers receive this data from sensors and then use it to send a command to the system's output devices. The output devices, such as actuators and relays, carry out the commands of a controller to adjust a system, for instance optimizing the flow of outdoor air to regulate indoor air quality (IAQ) and temperature., Communication protocols allow these systems to communicate with one another, and user interfaces allow humans to interact with the BAS by viewing system performance and energy data. A more detailed explanation of sensors, controllers, and communication protocols is given below.

BAS is typically categorized by their control function which is critical in order to understand the differences between standard and advanced BAS. The standard EN 15232-1:2017 defines a "BAC Control Function" as "the BAC effect of programs and parameters. BAC functions are referred to as control functions, I/O (input/output), processing, optimization, management and operator functions" and defines categories of building energy-related BAS functions that influence the energy use (CEN, 2017).

1.1.1 Management level

At the management level, all information from across other levels is collected, organized, aggregated, and presented uniformly to the operator. This is where any high-level management decisions are made. These may be from human or software operators. Analytics and performance reports are also generated at this level.

1.1.2 Middleware Level (Cyberphysical Level)

The middle level (or "middleware") bridges the physical and the cyber systems forming the "cyber-physical system" (CPS). This level and the distributed electronics integrate the different physical entities described below. The middle level or "automation level" includes all the infrastructure capable of applying a predefined scenario maintaining a control set point (Lilis, Conus, & Asadi, 2017).

1.1.3 Field Level

Includes all the end-devices and field buses which interface with the physical world. These typically include occupants, sensors and actuators, storage and generators, and smart grid.

Sensors: Are ICT technologies that can monitor different physical and environmental conditions in BAS. These sensors are deployed to conditioned spaces, building ducts, or mechanical equipment and send an output signal to a human system operator, a controller, or a centralized EMCS in order to adjust system action. Janez Moran et al. (2016) classify sensors into: Sensors for monitoring physical parameters such as indoor and outdoor temperature, human occupancy, lighting, humidity, CO2 concentration, and other sensors for monitoring consumption: gas, electricity, water; and movement of refrigerants. Advanced sensors, especially wireless sensor technologies, are helping to lower the cost of BAS because in buildings with wired systems, the numbers of cables necessary for connecting complex systems significantly increase installation costs. Rodrigues, Cardeira, and Calado (2010) note wireless sensors have a number of advantages, including reduced need for labor-intensive cable installation, reduced costs for power cables (as wireless technologies have internal batteries or use energy from the environment), and enhanced flexibility and reconfigurability. Still, because wiring costs contribute to nearly 45 percent of the installed cost for a BAS in a new building and 75 percent of the cost in a retrofit application, there are clearly significant cost benefits to be reaped from transitioning from wired to wireless technology for BAS sensors (Kintner-Meyer & Conant, 2004) (Wang, Law, & Lynch, 2005).

Controls: In buildings, control system controllers are often usually hardware and software that continually control physical actuators (such as lights and blinds) guided by management system commands or by measured variables (supplied by light or human-presence sensors) (Domingues et al., 2016). System or network controllers can direct mechanical systems such as an air handler unit (AHU), boiler, or chiller, and they can also be applied to sub-networks of controllers. Terminal unit controllers work at the level of individual devices, such as a heat pump, variable air volume (VAV) box, package rooftop unit, or lighting.

Since the 1980s, *Direct Digital Controls (DDC)* using software-based controllers have come to market due to increases in computing power and decreases in the costs of computing. This development has increased the flexibility and capabilities of controls while decreasing their implementation costs, which has increased their market penetration and enabled a wide range of energy-saving controls approaches (Roth, Llana, Westphalen, Quartararo, & Feng, 2006). DDC provides more effective control of building systems and can integrate these systems into one control loop, which leads to operational efficiency increases and optimized system performance.

Because the analysis in this report considers the costs and benefits of upgrading more conventional BMS, such as those operating with pneumatic or electric controls, to advanced BAS, a brief discussion of these types of controls is given here. Historically, the most popular control system for large buildings has been pneumatics, which essentially is a system powered by compressed air carried via copper or plastic tubes from a controller to a control device, such as a valve actuator. Pneumatic controls are capable of both "on-off" and "modulating" control and an provide adequate control for most simple HVAC control applications (Starr, 2015). Electronic controls function similarly to pneumatic controls except they receive a voltage signal that initiates the control sequence rather than a signal that is air-powered. The difference between electronic and DDC control systems is that the sensor input in DDC systems is converted to a digital form, where algorithms then perform the control (see explanation above).

Pneumatic and electronic controls are still used for building management, but DDC are the most common types of control systems in use today. The reason for this is that pneumatic and electronic controls cannot often achieve more complex control applications, such as fan synchronization of variable air volume (VAV) systems, integrating lighting control, or creating occupancy-based settings for building ventilation (Starr, 2015). Because this report advocates more advanced automation strategies in order to reduce energy consumption in commercial buildings, the analysis is predicated on conventional control strategies and systems being upgraded to enable DDC and even network-based approaches for building control.

1.1.4 Communications Protocols

System communication protocols play a key role in the performance of management, middleware, and field levels. Communications are critical to the functioning of a BAS and communication protocols dictate how different devices communicate with each other, as building controls operating at the whole-building level require communication between the system's sensors, controllers, and actuators in order to carry out appropriate actions. According to Domingues et al., the backbone of the field level is the fieldbus, a digital data system that allows communication between field devices such as controllers, sensors, and actuators. A fieldbus is an aggregator of communications and, once appropriate standards are used, several devices can share field bus connections to communicate with controllers. This therefore reduces installation costs by cutting down on the wiring. Devices on a fieldbus network also typically have some computational power allowing them to each replace several analog devices, further reducing installation costs (Domingues et al., 2016).

Open protocols also increase competition for different hardware and services, which helps reduce the costs of implementing BAS and brings a wider range of functionality to control technologies. Two of the most common communications protocols for interoperability of different equipment are BACnet™ and LonTalk®. BACnet™, short for Building Automation and Control Networks, serves HVAC, lighting, and fire alarm systems. The Building Automation and Control Networking Protocol (BACnet) (Bushby, 1997) was created for providing standardized communications. Typical communications needs include sensing, actuation, scheduling, alarms, analog hardware and software setting. BACnet is now the leading technology for building automation (Lilis et al., 2017)

Enterprise Systems for Network Integration: Enterprise refers to the integration of major building systems on a common network and it has emerged as way to address the often non-compatible and fractured nature of building operations systems. As defined by Buckman, Mayfield, & Beck, "enterprise is any method through which building use information is collected..." (Buckman, Mayfield, & B.M. Beck, 2014) (p. 102). In the context of building automation or management, enterprise systems can use real-time information to increase operational efficiency of building facilities and they are an important part of intelligent, connected buildings.

For instance, an enterprise system can receive information about a room booking in a university or school building and can then pre-program an adjustment to temperature and ventilation in that room based on the number of people who are likely to attend (Buckman et al., 2014). In this way, enterprise systems can increase the "intelligence" of buildings to adjust building conditions before occupants enter the building space rather than after, both saving energy and improving occupant comfort.

Enterprise systems and other wireless or network-integrated systems for building automation are likely to become predominant in most advanced BAS because of their benefits to building performance. Cloud components and Internet protocol (IP) will also allow for more interoperability and integration of building systems, trends that will certainly drive the growth of integrated BAS in commercial buildings in the future.

1.1.5 Different Approaches to Building Control Systems

Demand Controlled Ventilation:

DCV adjusts the intake of outdoor air (OA) based on measured CO2 levels in the building space (Roth et al, 2005) to maintain internal air quality (IAQ) in commercial building environments, and OA required to keep the building's air healthy and at acceptable IAQ levels.2 Demand Controlled Ventilation (DCV) is a controls approach that has a long history in the built environment, however BAS have integrated more technologies. In BAS, DCV uses carbon dioxide sensors, in conjunction with occupancy sensors, to detect the building's occupancy and adjust ventilation (Perry, 2017). DCV saves the most energy in buildings with highly variable occupancy as well as in climate zones that are more extreme because in moderate climates, the energy needed to condition OA is minimal. Some of the building types where DCV is appropriate include theaters, auditoriums, gyms, restaurants, retail, and places of worship. The energy savings of DCV in these types of buildings can be significant and very cost-effective. DCV can save an estimated 21% of energy used to introduce OA inside the building (Seventhwave, 2016). In a study from PNNL, simulations of the use of occupancy-based control (OBC) for HVAC systems and lighting in large commercial office buildings yielded a weighted average energy savings of 17.8 percent across 15 U.S. climate zones (Zhang, Liu, Lutes, & Brambley, 2013)

Occupancy Sensor-based Lighting Controls

Another application of controls and automation to commercial buildings is occupancy sensor-based lighting controls. As its name suggests, this control automatically turns lighting on or off according to occupancy levels, lowering the amount of time lights need to be turned on and thereby reducing total electricity consumption.

Occupancy-sensing technologies used in commercial buildings include passive infrared (PIR), ultrasonic, and acoustic, and lighting control. Products can either use one of these technologies alone or two together to increase optimization of the system. The system consists of a sensor and a power pack and, when the sensor detects occupancy, it sends a signal to the power pack to switch an internal relay and allow power to flow to the lights. Usually the system is configured so that it prevents frequent on-off switching during periods of rapidly changing occupancy, but false-triggering, which occurs when the occupancy sensor incorrectly switches lights on or off, is an issue that can in some cases prevents use of this technology. Despite this, occupancy sensors still have a high potential for energy savings in commercial buildings,

[2] ASHRAE 62-1989 "Ventilation for Acceptable Indoor Air Quality" is the broadly accepted standard for providing ventilation to maintain IAQ at acceptable levels.

though there is a wide range of possible savings depending on the type of space, occupancy patterns, behavioral patterns, and other factors (Roth et al., 2005).

Photosensor-based Lighting Controls

In a similar way that occupancy-based lighting controls reduce power consumption, photosensor-based lighting controls respond to the amount of visible light and can detect an increase or decrease in illuminance, which then enables an integrated controller to send a signal to the dimming ballast in order to increase or decrease the power flowing to the building's lighting systems. Building design and daylight patterns play a critical role in determining the efficacy of photosensor-based lighting controls, as savings are directly dependent on the amount of daylight received and the illuminance requirements of the building space. According to Jennings et al (2000), automatic daylight dimming has been shown in field studies to yield energy savings between 10 and 60 percent for private offices (Jennings, Rubinstein, DiBartolomeo, & Blanc, 2000).

These control strategies are examples of individual system-level controls that can reduce energy consumption from HVAC and lighting in commercial buildings. As discussed above, these individual applications are described to provide a clearer example of automation in commercial buildings. In most cases, BAS will integrate different lighting or HVAC controls that are most sensible for the building depending on type or function, size, and climate, among others. There is also a whole range of other automation technologies, especially those specific to automatic fault detection, diagnostics, and continuous commissioning. Table 1.2 below shows a list of different energy consumption reduction themes and relevant control and diagnostic technologies evaluated by the Pacific Northwest National Laboratories (PNNL) for its comprehensive analysis of building automation and controls.

Table 1.2 Common themes for reducing energy consumption in commercial buildings

Energy Consumption Reduction Theme	Relevant Technologies and Approaches
Automate Control Functions	• Lighting Control (based on occupancy sensing or photo-sensing) • Whole Building Control Systems
Eliminate Unnecessary Lighting	• Commissioning • Lighting Control (based on occupancy sensing or photo-sensing) • Whole Building Control Systems • Automated Whole Building Diagnostics
Eliminate Unnecessary Heating, Cooling and Ventilation	• Commissioning • Automated Whole-building Diagnostics
Fault Detection and Diagnostics	• Commissioning • Automated Fault Detection and Diagnostics (AFDD) for dampers, packaged rooftop units (RTU) • Automated Whole-building Diagnostics

Energy Consumption Reduction Theme	Relevant Technologies and Approaches
Reduce Excessive Outdoor Air Intake	• Commissioning • AFDD for dampers • Demand Controlled Ventilation • Duct Leakage Diagnostics • Automated Whole-building Diagnostics

Source: Roth et al, (2005, p. 2-8)

As mentioned previously, this report does not present a bottom-up analysis of the many different technologies and controls approaches common to building automation but rather considers the costs and benefits of an advanced BAS system across a range of different building functions and sizes. The Methodology Section describes this methodology and approach in its entirety.

Before discussing the market barriers and drivers for BAS, as well as the advantages and disadvantages of adopting BAS, a brief review of the current market for these systems is presented.

Energy Consumption and Efficiency Variables of BAS

The model inputs for energy and fuel efficiency factors are essential for calculating the reductions in energy use intensity in buildings with an integrated BAS. Estimated efficiency factors used come from Siemens (2009) which was derived from the methodology set out by European Standard EN 15232 (European Committee for Standardization, 2006). The table below shows these efficiency factors broken down by type of commercial building and by thermal and non-thermal purposes.

Table 1.3 Energy savings from commercial BAS

Building Type	Electrical Efficiency Improvement		Thermal Efficiency Improvement	
	High (Class B)	Advanced(Class C)	High (Class B)	Advanced (Class C)
Office	7%	13%	20%	30%
School	7%	14%	12%	20%
Hospital	2%	4%	9%	14%
Hotel	5%	10%	15%	32%
Restaurant	4%	8%	23%	32%
Retail	5%	9%	27%	40%

Source: IEA, (2013); Siemens, (2009).
Note: Highly dependent on ventilation demand for heating and cooling.

As these efficiency factors are critical to the model results, a short explanation of the assumptions used by Siemens (2009) in applying the methodology from EN 15232 to calculate energy savings from installing either a "high" or "advanced" BAS follows here.

Many commercial buildings have a conventional BAS that provides a base-level functionality and control over building systems, but these buildings will not see the same range of energy savings as more advanced BAS. The model considers the costs of upgrading a conventional BAS to an advanced BAS. Table 1.4 shows the four different efficiency classes of BAS that are defined in EN 15232. Table 1.5 provides a list of controls and management functions for Class C (Conventional) and Class B (Solution) buildings according to Standard EN 15232.

Table 1.4 Building automation efficiency classes as defined by EN 15232 and used to calculate energy savings potentials for BAS in Siemens (2009).

Class	Typical Energy Efficiency measures
A	High performance BAS and TBM: • Networked room automation with automatic demand control • Scheduled maintenance • Energy monitoring • Energy optimization
B	Advanced BAS and some specific TBM functions: • Networked room automation without automatic demand control • Energy monitoring
C	Standard BAS: • Networked building automation of primary plants • No electronic room automation, thermostatic valves for radiators • No energy monitoring
D	Non-energy efficient BAS (no longer allowed as per standard): • Without networked building automation functions • No electronic room automation • No energy monitoring

Notes: Siemens (2009) uses BAS to refer to Building Automation and Control Systems, though there is no discernible difference between this designation and BAS.
TBM: Technical Building Management

Table 1.5 Example of Minimum Detailed BAS functions and technologies for building automation efficiency classes.

Building Function or Field of Use	Building Automation Function	Reference Building (Class C)	Class B Building (EN 15232)
Heating	Heat Emission and Intermittent Control and/or distribution	Individual room automatic control by thermostatic valve or electronic controller with optimum start/stop	Individual room control with communication between controllers and to BAS and with optimum start/stop
	Hot water distribution network temperature	Outside temperature compensated control	Indoor temperature control
	Distribution pump control	Variable speed pump control	Variable speed pump control
	Generator control	Variable temperature depending on outdoor temperature	Variable temperature depending on outdoor temperature
	Generator sequencing	Priorities based only on loads	Priorities based on loads and generator capacities
Cooling	Cooling Emission and Intermittent Control and/or distribution	Individual room automatic control by thermostatic valve or electronic controller with optimum start/stop	Individual room control with communication between controllers and to BAS and with optimum start/stop
	Distribution pump control	Variable speed pump control	Variable speed pump control
	Interlock between heating and cooling emissions control	Partial interlock (dependent of the HVAC system)	Partial interlock (dependent of the HVAC system)

Building Function or Field of Use	Building Automation Function	Reference Building (Class C)	Class B Building (EN 15232)
	Generator control	Variable temperature depending on outdoor temperature	Variable temperature depending on outdoor temperature
	Generator sequencing	Priorities based only on loads	Priorities based on loads and generator capacities
Ventilation and Air Conditioning Control	Air flow control at the room level	Time Control	Human-presence Control
	Air flow control at the air handler level	On/Off time control	Automatic flow or pressure control
	Heat exchanger defrost and overheating control	With defrost and overheating Control	With defrost and overheating Control
	Free mechanical cooling	Night cooling	Free cooling
	Supply Temperature control	Constant set point	Variable set point with outdoor temperature compensation
	Humidity control	Supply air humidity limitation	Supply air humidity control
Lighting Control	Occupancy control	Manual On/Off switch + additional sweeping extinction signal (i.e. off at night)	Automatic detection Auto On / Dimmed
	Daylight control	Manual	automatic
Blind Control		Motorized operation with automatic control	Combined light/blind/HVAC control
Home Automation System, Building Automation and Control System		No home automation No building automation and control system	Centralized optimizing of the building automation and control system: e.g. tuning controllers, set points.
Technical Home and Building Management	Detecting faults of home and building systems and providing support to the diagnosis of these faults	Yes	Yes
	Reporting information regarding energy consumption, indoor conditions and possibilities for improvement	No	No

Source: EN 15232 and used in Siemens (2009).
Siemens' (2009) simplified method for calculating the efficiency factors of BAS assume that the reference case building is in Class C. Though this building does have an automation system, it does not include energy monitoring, and only primary plants are networked (rather than individual rooms). In the savings estimates above, Class B corresponds to "Advanced" building automation and control systems (BACS) and Class C corresponds to standard BACS.

The savings estimates above, then, are based on a reference case building with a standard BAS. The full range of efficiency factors are included in the model, but because these are reported in terms of electrical and thermal efficiencies, as well as by commercial building type, it is necessary to account for both of these nuances in the analysis.

1.2 ADOPTION PATH

1.2.1 Current Adoption

The current market for building automation and controls is undergoing renewed growth following the global recession of 2008. A report from Navigant Research projected that global revenue for commercial BAS is expected to grow from (US) $67.1 billion annually in 2015 to $102 billion in 2025 (after rising from $60 billion in 2013) (Navigant Research, 2014). Much of the demand is split even across the three areas: North America, Europe and Asia Pacific. BAS's market is concentrated in these three geographical areas with little penetration in other world regions.

This market forecast includes the two core BAS technology groups described in this study: BAS and TBM, and many other BMS for other non-energy systems. But the analysis in this report considers automation solutions that optimize energy consuming facilities within commercial buildings. For this reason, it is important to also discuss the current market for TBM or BEMS, as this grouping of technologies is often what market reports use when determining the growth of sensors and controls for energy management.

To estimate the current adoption of BAS, the team relied on market data from several different sources, including the Building Services Research and Information Association (BSRIA) (2014) and Memoori (2013), as well as reported data from the U.S. EIA (2012).

The U.S. EIA's *Commercial Building Energy Consumption Survey (CBECS) 2012* is used for current adoption in the U.S. The assumption (based on BSRIA (2014)) is that the EU has a similar percentage for current adoption of BAS, and also assumes, based on historical sales of BAS in China, that the size of China's commercial floor space with an advanced BAS is just over 7 percent of total commercial floor space. This is supported by a report from PNNL that indicates China's market for BAS is one-tenth the size of the U.S. market (Yu, Evans, & Shi, 2014).

While other reports do show existing BAS markets for other world regions, most of these remain quite small compared to the U.S., EU, and, to a lesser extent, China. Because of the difficulty of verifying any of these data and because market revenue or sales data do not often correlate clearly with the model's metrics (i.e. with total commercial floor space with a BAS), other regions are not considered.

Global current adoption was estimated at around 57% of the TAM (in terms of floor area).

1.2.2 Trends to Accelerate Adoption

The adoption of BAS will be accelerated by several trends. The following trends are presented in decreasing level of relevance:

<u>The rise of Smart Buildings and the IoT:</u> The first trend that will increase the adoption of advanced BAS is the growing demand for smart building systems. Consumer Internet of Things (IoT) devices have drawn the most attention, but according to a research report from the Deloitte Center for Financial Services, "it is enterprise-level adoption of the technology that will likely have the bigger impact on [the Commercial Real Estate (CRE)] industry" (Kejriwal & Mahajan, 2016). The report argues that the CRE industry is positioned to implement IoT technologies within commercial BMS in order to enhance both building performance and

user experience. This trend will likely increase the awareness and perceived usefulness of BAS solutions among business owners, thereby helping to accelerate adoption.

Enhanced Occupant Satisfaction: This has historically been the primary objective for building owners both to increase the comfort and productivity of building occupants while also increasing tenant retention. A recent study by WGBC indicates that sample office buildings achieved over £200,000 in savings a year from lower staff turnover and sickness (WGBC, 2018). In this sense, BAS can significantly increase their market penetration in the future by enhancing the core business or function of commercial buildings. Understanding and documenting how productivity is linked to optimized lighting, HVAC, and IAQ control can position BAS vendors to make a stronger case for investment in these solutions.

Reduces Total Cost of Ownership (TCO): BAS is also valuable for building owners and operators because they can reduce the need for operations and maintenance expenditure. These savings can be achieved by individual tenant billing for services facilities, remote monitoring and control of the systems in the building, improving maintenance enabling corrective and predictive actions, and monitoring and optimizing energy efficiency (Morán et al, 2016). Reducing energy consumption is perhaps not the primary concern for building owners, but it is important nonetheless, and although utility expenses typically make up a very small proportion of total building expenses, they do often account for a large proportion of building operating expenses. Studies have reported that BAS can generate an average net savings potential across the EU of 15% to 22% from all building energy consumption (Tichelen et al., 2018). In the US, BAS technologies can save the average office 18% in heating, cooling and ventilation, 28% in plug load, and 33% in lighting energy (Perry, 2017). Furthermore, the value proposition for the energy-saving aspects of BAS is improved in regions that have higher electricity prices and specific charges for peak electricity consumption. According to Brown and Koomey (2002), lighting and HVAC account for 75 percent of commercial sector peak electricity demand, so optimizing the use of both of these systems during periods of peak demand can result in even greater savings for the building owner. Two other advancements in energy management that can yield significant cost savings for commercial buildings are the use of automatic fault detection and diagnosis (AFDD) and continuous commissioning (Bansal, 2018). An Advanced BAS equipped with DDC allows an operator to make preventative changes to building systems through an interface or dashboard rather than having to manually modify an individual system's settings, and this can save the building manager time and can lead to a reduction in maintenance calls (ACHRN, 2002).

HVAC and lighting equipment manufacturers have started to integrate controls functions into their products. HVAC equipment manufacturers traditionally have been slow in responding to advances in controls and communications; however, in recent years, this trend has reversed with a vast range of products with very different control and communication capabilities (Waide Strategic Efficiency Limited, 2014) .

Integration of advanced security systems with energy management systems within BAS. Centralized systems are often better suited to address security breaches that impact building facilities and, given that security and safety automation are rapidly increasing technologies in commercial buildings, the extent to which BAS can envelop this market potential could prove beneficial for the long-term growth of this solution.

Legislation that encourages efficient retrofits of the existing commercial building stock could also support further adoption of BAS as a legitimate solution for reducing building emissions. For instance, a report from the European Union Building Automation Controls Association (EUBAC) argues that the EU's Energy Performance of Buildings Directive (EPBD 2010/31/EU) does not go far enough in encouraging Member States to pursue building automation and controls and that Member States have fallen short in implementing recommendations for building automation that are currently contained in EPBD (EUBAC, 2016). In addition, common buildings codes and standards, such as ASHRAE 90.1 in the U.S., can be updated to mandate minimum controls infrastructures in commercial buildings, especially small- and medium-sized buildings. This would require building owners and operators to put in place the architecture for more advanced BAS and could help speed adoption of these systems throughout the commercial building stock (Katipamula, Rejmanji, & Bisbee, 2011)

BAS will be made economical for small businesses: This is a technological trend that depends on the ability of BAS developers to build systems that are not too cost prohibitive for businesses that are smaller than 50,000 ft^2 (4,650 m^2). There is evidence, however, that developers are beginning to create systems that are fitting for smaller commercial applications and can provide similar energy savings and occupancy comfort benefits as those in larger commercial buildings (Lux Research, 2012; Sofos, 2016). This is of critical importance to the growth of BAS in the commercial building sector, as buildings that are <50,000 ft^2 (<4,650 m^2). contribute about 95 percent of the commercial building stock and about 50 percent of the commercial building floor space in both the U.S. and Europe (BSRIA, 2014)

1.2.3 Barriers to Adoption

BAS face several key market barriers. The following barriers are presented in decreasing level of relevance:

Functionality gaps and lack of commonly agreed field-knowledge: According to Lilis et al., open standards are not enough to solve the increasing interoperability issues surrounding intelligent buildings. As an example, "open" does not imply "free" in relation to major automation standards. Echelon (LonWorks standard) for instance, requests royalty fees for every device using their Neuron Chip; these initial fees for the smaller vendors may be prohibitive (Lilis et al., 2017).

Specialized installation, programming, and O&M: When a BAS application does not yield its projected energy and cost savings, the credibility of the entire system falters. Numerous reports of BAS not meeting their energy-saving potential in commercial buildings—whether due to specific building conditions or improper installation—are another major barrier to adoption, and, given the high upfront costs of complex BAS, low confidence among building owners about the credibility of installing these systems can prevent them from achieving significant market penetration. The actual performance of BAS can make building managers skeptical of these technologies and can inhibit further deployment.

Lack of knowledge among building owners and decision-makers about how BAS and properly installed BAS can benefit them**:** Tichelen et al. (2017) summarize the knowledge gap among building owners as limited awareness of the energy saving potential; information barriers on selection and specification of advanced BAS; confusion about the choices available and benefits; limited willingness to invest in BAS when there are doubts about the performance benefits (p.9). A study by Lowry (2002) found that more than half of the building EMCS operators surveyed had three days or fewer of training, and this general lack of knowledge often leads building operators to become frustrated with a new system they do not understand and consequently prevents them from using it in the most optimal and efficient way. This reduces the performance of the system (Lowry, 2002)

Several final barriers to BAS adoption at the entire system-level include interoperability issues. In buildings that are let, owners usually do not have as much motivation to pay for costly energy saving retrofits, such as installing BAS components, because owners do not pay energy costs for the building. Additionally, most of the time, tenants do not care about energy expenses enough to either pay for efficiency upgrades themselves or encourage the owner to do so. Despite the breadth of communication protocols that have been developed to integrate different sensor and control technologies manufactured by different companies, there are still some concerns that these technologies are not always interoperable, which can hamper the market for add-on software and services specific to BAS while also lowering the overall competitiveness of individual markets for sensors and controls (Roth et al., 2005).

Briefly, there are also barriers that exist specific to individual systems, including those discussed in the previous section. Concerns about the cost of CO_2 sensors and issues related to calibration of these sensors represent the greatest barrier to further deployment of DCV systems, and, in the case of occupancy-based lighting controls, the barriers are primarily related to cost, sensor lifetime, and occupant frustration with lighting sensors that are prone to false triggering, thus bothering users of the space while also leading to increased complaint calls to building managers.

1.2.4 Adoption Potential

Data on both existing adoption of BAS and future adoption of BAS in commercial buildings is almost non-existent. This is likely due to the difficulties of defining BAS in different world markets given that the term refers to a suite of technologies rather than individual components.

Determining the potential for emissions reductions in the building sector is a way to project the growth of BAS, as these are central to emissions reductions for commercial buildings. Several recent efforts within the industry have advocated for the need to reach net-zero emissions in the commercial building stock in order to follow through on the ambition of the Paris Climate Agreement.

Both *Architecture 2030* and the *World Green Building Council* (WGBC) 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 (WGBC, 2016). Architecture 2030's *Roadmap to Net Zero Emissions* (2014) sets 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 from other legislation regarding emission reduction pathways for buildings in the U.S. and the EU. The U.S. Energy Independence and Security Act of 2007 (Section 433) and Executive Order 13423 require all new Federal buildings and large renovations to be zero carbon by 2030 and direct 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).

Given these efforts and similar initiatives around the world to reduce all net emissions to zero in the global building stock by 2050, one may assume that the adoption of BAS in commercial buildings will likely be close to 100 percent by the mid-point of the century. In both new and existing commercial buildings, BAS is a solution that can lead to significant emissions reductions and is, therefore, essential for net zero buildings.

Both the market for BAS and the market for TBM are growing, and according to Lux Research, the U.S. market for sensors and controls for BEMS will reach $2.14 billion in 2020; in Europe the market will reach $1.93 billion (Lux Research, 2012). Navigant Research (2015b) projects a global demand of almost $11 billion in 2024.

It is clear that the market for TBM is a much smaller subset of the overall market for BAS, and, importantly, the market share for TBM technologies between different countries is also quite different. Considering just the market for TBM, the USA and EU comprise over 84 percent of the market (BSRIA, 2014). Lux Research also predicts a shift away from a BAS-dominant to a TBM-dominant market in the coming decades.

In 2005, only about 10 percent of the commercial buildings in the U.S. (or about 33 percent of the total commercial floor space) had a centralized EMIS, and the 2005 PNNL report noted that a central challenge to scaling up the adoption of such systems was the fact that they were often not cost effective for smaller commercial buildings, typically those smaller than 50,000 ft^2 (4,645 m^2) (Roth et al, 2005).

Recently, however, a shift has occurred in the commercial TBM market as developers have embraced advanced BAS that are appropriate for buildings smaller than 50,000 ft^2 (4,645 m^2). This is a critical building market, since the average office building in the US, for instance, is 16,000 ft^2 (1,486 m^2) (U.S. EIA, 2012) and these typically do not include BAS technologies, thus providing unique opportunities for smart energy savings (Perry, 2017) p. 19. Lux Research estimates that the number of small commercial buildings with TBM will be almost 40 times what it was in 2012 by 2020 and that 40 percent of the U.S. market for TBM will come from these small commercial buildings.

Finally, there is current consensus that the majority of all market opportunities for BAS is in retrofit. According to the Building Services Research and Information Association (BSRIA), this is the case in both the EU and U.S. (BSRIA, 2014). This is explained by several reasons. First, according to Dill et al., in the US from 2003 to 2008 for instance, the office construction market focused primarily on new office construction. However, after the Great Recession (2007-2009), this situation reversed with nearly twice as many renovation projects in the US as there were "new building" projects by 2016 (Dill, Durham, & Foley, 2017). Secondly, in many cases, purchasing new HVAC or lighting equipment with smart controls will be more cost-effective than retrofitting equipment in existing buildings since for a small additional cost, most manufacturers offer a smart version of the original equipment that would offer significant benefit (Perry, 2017). Given that these technologies are particularly suited for retrofit applications, this opportunity further primes the market for wireless sensor and control technologies,.

1.3 ADVANTAGES AND DISADVANTAGES OF BAS

Table 1.6 Technology Comparison

	Installation Costs	Operations & Maintenance Costs	Ability to Save Energy and CO_2	Complexity for Building Manager
Conventional Building HVAC	Low	Medium	Low	Low
BAS	High	Medium	High	High
Net Zero Buildings	High	High	High	High
Smart Thermostats	Medium	Low	High	Low

The previous section discussed in detail some of the primary barriers, drivers, and trends in the global BAS market, and many of these are directly related to the advantages and disadvantages of BAS. This section describes how BAS is a similar solution to some other approaches to reducing the energy consumption of commercial buildings and then discusses the additional benefits and burdens of adoption.

1.3.1 Similar Solutions

A solution that is often discussed in the literature that will likely benefit from growth and maturity of BAS technologies is net zero- or positive energy-buildings (NZEB, PEB). A NZEB or PEB refers to a building with zero or net-negative energy consumption over a year, and this is usually achieved through a combination of reduced annual power demand (primarily from the deployment of highly energy efficient technologies) and the generation of enough power to meet this demand from renewable energy sources (Kolokotsa, Rovas, Kosmatopoulos, & Kalaitzakis, 2011). Most analyses of NZEB/PEBs assume that "intelligent" energy management using advanced sensors, controls, and monitoring systems is a core component of these buildings. BAS, then, is a solution that is integral to the development of NZEB/PEB, but, as discussed, BAS provide a significant opportunity in commercial building retrofits given the large percentage of commercial buildings without a BAS or BEMS.

Energy efficiency technologies, including those such as HVAC efficiencies, LED lighting, refrigeration management, smart thermostats and others, have similar effects as BAS, and, while it is true that commercial buildings with incredibly efficient technologies will likely not benefit as much in terms of energy savings from the installation of a BAS, these sets of technologies are still not contradictory in any way, and both can be used to generate savings within commercial buildings. In fact, within the realm of SEB, Home Energy Management (HEM) systems (smart networked devices that can provide information on, and dynamically adjust home energy use) have been evolving for decades and appear poised to enter the mainstream with the strong introduction of smart thermostats (Snell & Source, 2016).

1.3.2 Arguments for Adoption of BAS

Energy savings, enhanced occupant satisfaction, and reduced cost are the primary advantages of BAS. Increasingly, wireless sensor and control technologies can be more easily integrated into existing buildings so that even large commercial buildings with many different HVAC zones can benefit from greater efficiency and optimization. Compared to other energy efficient technologies, BAS can reduce the consumption of the entire energy system within a commercial building and can simultaneously improve occupancy comfort and worker productivity.

1.3.3 Additional Benefits and Burdens of BAS

Other advantages of BAS and the wider adoption of advanced BAS include:

Employment Creation: 1.3 to 2.1 million jobs can potentially be created in the next two decades across the EU if EU-wide BAS deployment were to occur through perhaps an incentivization framework (Debusscher, 2017) .

Improved building security: given that a BAS can be programmed to lock doors, monitor building spaces, detect fires and other security breaches, and notify appropriate personnel should any problems occur.

Enhanced building operations and maintenance that can prevent costly interruptions to business activities: and greater convenience for building operators or managers because an operator can monitor and adjust all of the different building facilities (or even facilities in separate buildings) from a centralized dashboard or interface.

The primary disadvantage of a broader implementation of BAS are:

The upfront cost of BAS technologies, as well as the centralized computer system and software necessary for managing the BAS: However, recent trends in wireless technologies and enterprise communication networks suggest that the cost of BAS will continue to decrease, thus making these systems more suitable for smaller commercial buildings rather than only fitting for buildings larger than 100,000 ft^2 (9,290 m^2, Roth et al., 2006). Several financing methods are available that can help overcome investment barriers. One of these is an Energy Performance Contracting (EPC), which enables a commercial client to pay for the capital improvements of a project (in this case, for BAS upgrades) through the income of cost savings, which are based on the energy performance of the building after it has installed energy efficiency technologies. In these contracts, it is often an Energy Service Company (ESCO).

Specialized expertise for programming and managing the BAS technologies: This can present a burden to building managers and maintenance crews when the BAS needs to be fixed if it was installed incorrectly or if ongoing maintenance issues persist. In addition to the system complexities, the ability for BAS to truly optimize building performance relies on the effective utilization of significant quantities of data that are generated by the system. If this data is not applied by building managers to optimize building performance, then these buildings will likely not reap the full benefits of automation (Xiao & Fan, 2014).

2 METHODOLOGY

2.1 INTRODUCTION

Project Drawdown's models are developed in Microsoft Excel using standard templates that allow easier integration - 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 constitutes the results.

The overarching approach to modeling BAS is based on the functional unit of million square meters of commercial floor space[4]. The implementation unit is the same as the functional unit to provide most flexibility in adoption measurement. The agency perspective used is that of building owners and managers, who are assumed to be the key decision makers on installing BAS. Adoption was projected using simple regional growth curves due to lack of prognostication data in the literature. The 2050 adoption value for each Drawdown region was set based on an assumed adoption rate relative to either the base year adoption of US or that of the EU. Most cost and emissions inputs are based on data from these two regions, though some data applicable to China was used.

2.2 DATA SOURCES

The data used in this model come from a variety of sources, including peer-reviewed publications, agency and institutional reports, and market analyses. For most variable inputs, a meta-analysis of existing data points in the literature is used to create low, mean, and high estimates. The model conducts a sensitivity analysis of, on average, five data points from the literature and, in some cases, as many as 20. The quantity of data allows calculation of robust and reliable inputs for the analyses that range from conservative to optimistic estimates for the costs and benefits of adoption.

In order to project the growth of global commercial building floor space (in million m^2), the data from the Integrated Building TAM model relies on existing estimates from IEA (2013) and from the Global Buildings Performance Network (GBPN), namely from (Urge-Vorsatz et al., 2015). These data sources are also used to project the growth of commercial building floor space on a regional basis, creating estimates for OECD90, Asia (sans Japan), Middle East & Africa, Latin America, and Eastern Europe. Finally, several country-level sources were used to project the TAM for China, India, and the U.S. (Hong et al, 2014; Kumar et al., 2010; Chaturvedi et al, 2014; EIA, 2016). To project the TAM for the EU, data from the Buildings Performance Institute Europe is used (BPIE, 2011; and Boermans et al., 2012).

First cost data for the installation of BAS in commercial buildings was not commonly reported in peer-reviewed literature nor by the automation and control industry, so most cost estimates were taken from case studies of existing BAS projects covering a range of different types of buildings. Several of these sources come from reviews conducted by the Sustainability Roundtable, Inc. (2012).

Operating costs, which are assumed to be the total commercial building expenditure on electricity and fuel per million m^2 of commercial floor space, are calculated using data on the energy intensity of commercial buildings across a variety of types; this data primarily comes from IEA (IEA, 2013). Another source that

[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 adoption 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.
[4] "Commercial" is taken to mean all non-residential and non-industrial buildings inclusive of retail, restaurants, hotels, hospitals, schools, and offices.

was used for average energy intensity of commercial buildings was a comparative analysis of building energy consumption around the world (Hinge, Bertoldi, and Waide, 2004). It was also necessary to determine average values for commercial energy intensity for thermal and non-thermal purposes; so IEA (2013) data for the breakdown of energy consumption by end-use and by fuel was also used.

2.3 TOTAL ADDRESSABLE MARKET

Projecting the growth of commercial building floor space is essential to determining the potential adoption of BAS globally. The model relies on two global projections for commercial floor space and a sensitivity analysis of these two projections enables us to select a trend and rate of TAM growth through 2060. A 3rd degree polynomial curve with a medium growth rate (R^2=0.99) is used to project future additions of global commercial floor space. Table 2.1 shows the model inputs for TAM taken from the literature and Figure 2.1 shows the calculated projection for the TAM from 2020 – 2060.

Table 2.1 Growth in commercial floor space globally from 2010-2060 (million m^2)

Data Source	2010	2020	2030	2040	2050	2060
IEA (2013)	37,633	43,908	52,124	57,449	62,514	67,061
Ürge-Vorsatz et al. (2015)	49,800	62,700	74,500	86,500	92,700	99,520

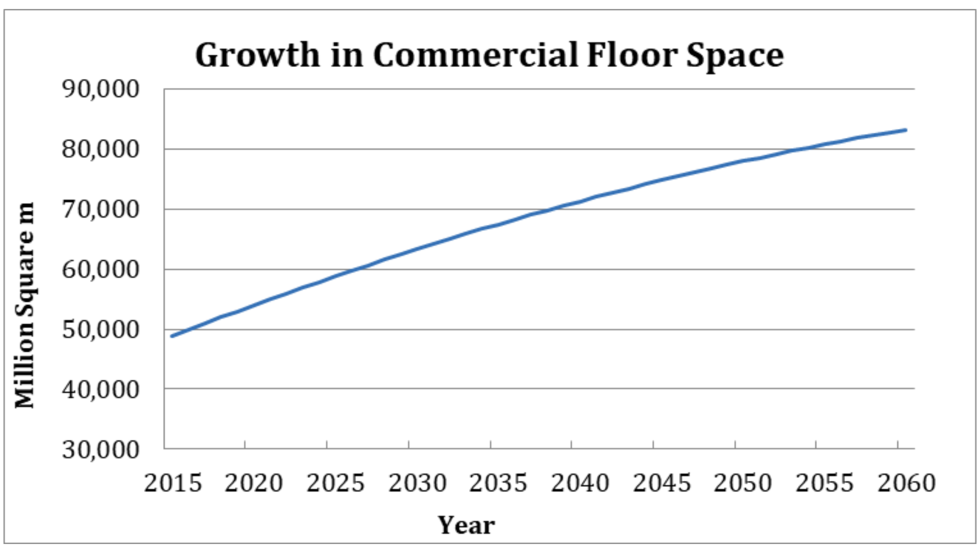

Figure 2.1 Modeled growth in Commercial Floor Space from 2015-2060

These estimates diverge considerably as the projections for global commercial floor space in the Ürge-Vorsatz et al. (2015) publication show a much larger growth over the coming century. This discrepancy highlights the differences in methodology.

2.4 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.

Though BAS have been commonly deployed in large commercial buildings in regions such as North America and the EU, there is very little reliable data for either the current or future adoption of BAS in most regions. Market research reports provide the best estimates for future growth of BAS but many of these reports do not project market development beyond 2025. For this reason, it was necessary to use several key assumptions in calculating both current and future adoption globally.

2.4.1 Reference Scenario

This model defines the REF adoption scenario as a fixed percentage of TAM over the modeling period using the percentage of adoption in the base-year as the fixed percentage of TAM projecting forward.

2.4.2 Project Drawdown Scenarios

The PDS global adoption scenarios are based primarily on several sources that have set ambitious calls for the growth of net zero or zero energy buildings (NZEB). These include the World Green Building Council's initiative *Advancing Net Zero* (WGBC, 2016) and Architecture 2030's *Roadmap to Zero Emissions* (Architecture 2030, 2014). It is assumed that the penetration of advanced, integrated BAS can reach 95 percent[5] of the global commercial building stock by 2050. Each PDS scenario sums expected adoption in each region. Regional adoptions were selected based on existing and expected max adoption for that region which was guided by the 95 percent global maximum.

Plausible Scenario

The Plausible Scenario sums logistic S-curve prognostications for each Drawdown region. The 2050 adoptions in each region are shown in Table 2.2.

Drawdown Scenario

The Drawdown Scenario sums linear prognostications of adoption for each Drawdown region. The 2050 adoptions for each region are shown in Table 2.2

Optimum Scenario

The Optimum Scenario sums linear prognostications of adoption for each Drawdown region. Table 2.2 shows the 2050 adoptions.

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[5] Estimated global penetration is 95 percent rather than 100 percent to account for the fact that it will likely be incredibly difficult to reduce 100 percent of emissions from the commercial building stock, especially in developing countries. In addition, it is possible that not all zero energy buildings will have a BAS, as some may have substantial deployment of on-site renewable energy, which might preclude the need for an advanced BAS to reach net zero emissions.

Table 2.2 Summary of 2050 Adoptions in each Region for PDS Scenarios

Drawdown Region	Adoption in 2050			Rationale
	Plausible Scenario (Logistic S-curve)	Drawdown Scenario (Logistic S-curve)	Optimum Scenario (Linear)	
OECD in 1990	100%	100%	100%	Already a high adoption is seen in US and EU, and growth is mainly here.
Eastern Europe	21.3%	50%	80%	Assumed to meet 50% of current EU level in Plausible Sc.
Asia (sans Japan)	44.8%	80%	80%	Assumed to meet current US level in Plausible Sc. Driven by high adoption in China.
Middle East and Africa	8.5%	50%	80%	Assumed to meet 20% of current EU level in Plausible Sc.
Latin America	22.4%	50%	80%	Assumed to meet 50% of current US level in Plausible Sc.

2.5 Inputs

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

2.5.1 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 in the literature review.

To account for the difference in electrical and thermal efficiencies, as well as to account for the fact that commercial building energy consumption by fuel type and end-use varies quite significantly across building type and region, the percentage of commercial energy end-uses strictly using electricity is first determined. To calculate this percentage, data from IEA (2013), which breaks down energy use for commercial buildings by end-use, is used. Data collected indicate that, on average, 73.9% of commercial building energy consumption is for non-thermal purposes, including all other end-uses other than space heating or cooling. The remaining 26.1% of commercial energy consumption is used specifically for thermal purposes.

The next step was to determine how much of that thermal commercial energy consumption is for space heating vs. space cooling, again using data from IEA (2013), and further, the percentage of space heating, on average, that is from electricity vs. fuel.[6] After making these calculations, the total electricity

[6] In this model, fuel consumed for space heating is assumed to be a mix of natural gas, oil, biomass, and coal, the shares of which were identified from research at the global level (the largest for 2013 was 35% natural gas).

consumption in commercial buildings, as well as the total fuel consumption (which was assumed to be used only for space heating, or “thermal purposes”), is calculated.

One last step is required before determining the electrical and fuel efficiency factor inputs for the model. Because energy use intensity in commercial buildings varies considerably both across different regions and countries, as well as between different types of commercial buildings, it is necessary to create a weighted average efficiency factor for thermal and non-thermal end-uses based on the share of floor space globally for each of the building types listed above. While a breakdown of commercial building floor space regionally by building type was not available for all regions or countries, data for Europe, U.S., and China were found, and, because it was expected that most adoption of BAS will occur in these three markets, total commercial floor area (in the base-year) for each of these regions was aggregated by building type to determine the percentage share of commercial floor space in these three regions for each building type. These percentages are used to weight the efficiency factors from Siemens (2009) above.[7]

After calculating commercial building electricity consumption (converting to TWh/million m^2/yr), the weighted average efficiency factors were applied to determine the electricity savings potential for the “advanced” BAS as compared to the “conventional” BAS. Importantly, because electricity is used for both thermal and non-thermal purposes, the weighted averages for both of these was included in the input for the electricity efficiency factor and then weighted by the share of commercial building consumption for non-thermal purposes and thermal purposes.

In calculating the reductions in fuel consumption in buildings with an advanced BAS, a similar approach as above was taken. The total fuel consumption in the “conventional” or “reference” building was converted to TJ/million m^2/yr and then a weighted average efficiency factor for thermal purposes was applied. The weighted average efficiency factor for electrical purposes is not included because it is assumed that fuel is only used in commercial buildings for thermal purposes (primarily space heating). Table 2.3 *below* lists the model’s inputs for commercial electricity and fuel consumption as well as the weighted average electricity and fuel efficiency factors.

Lifetime Variables

Several additional variables were necessary to calculate the financial benefits of installing advanced BAS in commercial buildings. These include estimates for the life expectancy of both conventional building sensors and controls as well as advanced BAS technologies. Though life expectancies for these technologies can vary considerably based on numerous factors, the model uses data from FannieMae (2014) for the Estimated Useful Life (EUL) of conventional building controls and HVAC industry data for the life expectancy of DDC automation systems.

Table 2.3 Technical model inputs.

[7] Because “Other” was a category of building type that was prevalent in the data for Europe, the U.S., and China, but not prevalent in the efficiency factors used by Siemens (2009), this total floor space was distributed evenly across the remaining building types.

Variable	Unit	Project Drawdown Data Set Range	Model Input	Data-points (#)	Sources (#)
Commercial Weighted Average Energy Consumption	$kWh/m^2/yr$	210.1-332.6	271.4	10	2
Commercial Building Energy Consumed for Thermal Purposes	percent	10.5%-41.6%	26%	5	1
Electricity Consumed by Conventional Commercial Building	$kWh/m^2/yr$	204-204	204	1	Derived from other inputs
Fuel consumed by Conventional Commercial Building	$GJ/m^2/yr$	242,946-242,946	242,946	1	Derived from other inputs
Weighted Average Electrical Efficiency Factor	Percent	2.4%-22%	Depends on Scenario	12	2
Weighted Average Thermal Efficiency Factor	percent	14.8%-32.9%	Depends on Scenario	12	2
Lifetime of conventional technology	years	25-30	27.5	2	2
Lifetime of solution technology	years	11.9-23.1	17.5	4	1

Sources: IEA, 2013; U.S. EIA, 2012; BPIE, 2015; Hong et al., 2014; Siemens, 2009

2.5.2 Climate Inputs

The climate analysis in this model uses the values for annual energy intensity of commercial building floor space and reductions in energy consumption from BAS installation (which are general "Technical" inputs in the Technical Inputs section). To calculate key model results, the model uses reported emissions factors for both electricity and fuel. Emissions factors for electricity generation are derived from the projected energy generation mix from three AMPERE RefPol scenarios in IPCC AR5 model Database (GEM3, IMAGE, MESSAGE) and the IEA's ETP 6DS scenario, and direct/indirect emissions factors by generation type taken from the IPCC AR5 Model Database, AMPERE3-MESSAGE Base scenario. The reader should note that since this combined reference projection includes a shift away from coal and oil to natural gas, the emissions factors decline slowly over the analysis period. Fuel emissions factors are calculated using the methodology recommended in the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Volume 2, Annex 1. The values used are shown in Table 2.4.

To calculate the climate impacts of BAS adoption in the PDS scenario, estimations were made of the total reduction in both electricity and fuel consumption for thermal and non-thermal purposes per million m^2 of commercial building space with a BAS. Emissions factors for grid electricity and fuel are applied to calculate maximum annual emissions reduction, total emissions reduction, and concentration change (in PPM equivalent). Then emissions reductions are calculated using the following equation:

$$CO_2reduced = (Reduction\theta_{PDS}) \cdot (G_{ef}) + (Reduction\delta_{PDS}) \cdot (\mathrm{F}_{ef})$$

where:

- $CO_2 reduced$ is the CO_2-eq emissions reduction (in metric tons) associated with the reduction in annual energy consumption in commercial buildings in each PDS scenario.
- $Reduction\theta_{PDS}$ is the reduction in electricity consumption intensity (TWh/million m^2/yr) for both thermal and non-thermal purposes in commercial buildings. These include electric space heating, space cooling, water heating, lighting, computing, office equipment, ventilation, refrigeration, and other end-uses.
- G_{ef} is the emissions factor (in metric $t CO_2$-eq per TWh) of grid electricity globally for each year.
- $Reduction\delta_{PDS}$ is the reduction in fuel consumption intensity (TJ/million m^2/yr) for space heating in commercial buildings in each PDS scenario.
- F_{ef} is the fuel emissions factor for natural gas (in metric $t CO_2$-eq per TJ).

Table 2.4 Climate Inputs

Variable	Unit	Project Drawdown Data Set Range	Model Input	Data Points (#)	Sources (#)
Global average REF Grid Emissions Factor	g CO2e/kWh	503-593	Depends on year. Starts at High Input in 2020 & declines to Low Input in 2050.	12 each year	4
Combined REF Space Heating & Cooling Fuel Emissions Factor	t CO2e/TJ of fuel	87.04-87.04	87.04	8 including individual fuel emissions factors and shares	1

2.5.3 Financial Inputs

To calculate operating costs from commercial building energy consumption in both the PDS scenarios, the model uses a range of simulated energy savings estimates for BAS from Siemens (2009) which are also reported in IEA (2013) *Transition to Sustainable Buildings: Strategies and Opportunities to 2050*. These estimates are based on the European Standard EN 15232: *"Energy performance of buildings – Impact of Building Automation, Control and Building Management*," which specifies methods to assess the impact of BAS on the energy performance of different classes and categories of buildings (European Committee for Standardization, 2006). The model calculates energy costs using a global weighted average commercial electricity price based on historical price data from EIA and IEA normalized to 2014 USD. For fuel prices, the model uses a share-weighted average price based on spot prices of heating fuels: natural gas, oil, coal, and biomass from 2005-2014.

The PDS scenarios for global BAS adoption models both the capital costs of installing a BAS as well as the operating costs in each year of analysis. The capital cost or first cost represents the total financial costs to a commercial building owner for purchasing and installing an advanced, integrated BAS. Annual operating costs in both the REF and PDS scenarios are assumed to be the costs to the building for energy, including electricity and fuel. The model calculates annual operating costs using the energy savings, applying weighted average global prices for commercial electricity (per TWh) and fuel (per TJ) to calculate annual savings.

As was mentioned previously in this section, cost data for BAS was very limited, so a range of different cost data were taken from a number of different BAS case studies. To calculate the "conventional" first cost for a reference case BAS - assumed to operate using pneumatic or electric controls rather than DDC - data from Sustainability Roundtable, Inc. (2012) was used. Then this percentage is applied to the "solution" first cost to calculate an average cost for conventional BAS.

There is also limited data available for estimates of the decline in prices for sensor and control technologies, which often comprise a substantial portion of the installed cost of BAS. According to Kintner-Meyer & Conant (2004), the cost declines, especially for wireless sensor technologies, might be significant, so it is appropriate to use a learning rate in the model to project a decreasing installed cost for BAS. But, given the lack of any concrete data on price declines, the learning rate used in the model is based on an assumption that it will be similar to other types of energy demand or efficiency technologies (Weiss et al, 2010). Table 2.5 and Table 2.6 show the model inputs used to calculate the financial costs and savings annually for commercial BAS adoption.

Table 2.5 Financial Inputs for the Conventional Technology

Variable	Unit	Project Drawdown Data Set Range	Model Input	Data Points (#)	Sources (#)
Installation Cost/ First Cost	US\$2014/m^2	10.34-24.69	17.51	5	5
Annual Operating Cost	US\$2014/ m^2/yr	22.9-22.9	22.9	1	Derived from other inputs
Discount Rate for Future Cash flows	percent	6.1-12.3	9.68	5	4

Table 2.6 Financial Inputs for the Solution Technology

Variable	Unit	Project Drawdown Data Set Range	Model Input	Data Points (#)	Sources (#)
Installation Cost/ First Cost	US$2014/m^2	16.20-29.27	22.74	20	6
First Cost Learning Rate	percent	10%-10%	10%	1	1
Annual Operating Cost	US$2014/ m^2/yr	20.2-20.3	Depends on scenario	3	Derived from other inputs
Discount Rate for Future Cash flows	percent	6.1-12.3	9.22	5	4

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: infrastructure required for the solution is available and in-place, necessary policies 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 first costs may change according to learning. Full details of core assumptions and methodology will be available at www.drawdown.org.

Beyond these core assumptions, there are other important assumptions made for the modeling of this specific solution. These are detailed below.

Assumption 1: The costs and savings for installing a commercial BAS are similar for all sizes and all types of commercial building.

- This simplifies the calculations
- Cost data for commercial BAS was not differentiated by building type; instead, a range of cost data from the literature for BAS installation in different commercial building types was used.

Assumption 2: The conventional BAS market consists of both commercial buildings without a BAS as well as those with a BAS using more traditional control methods, such as pneumatic or electronic controls.

- Required due to the lack of reliable data on the differences between adoption of conventional and "advanced" BAS.
- Uses the same approach as Siemens (2009).

Assumption 3: Energy efficiency factors contained in this model represent the expected energy savings that might accrue in buildings with either a "high" or "advanced" BAS.

- It is not possible to predict what types of BAS applications will be appropriate for specific commercial buildings.
- Uses the same approach as Siemens (2009).

Assumption 4: All energy consumed for space cooling purposes is assumed to be electric and all non-electric (fuel) energy consumed for space heating is assumed to be a combination of existing space heating sources (natural gas, oil, biomass and coal).

Assumption 5: Indirect emissions are not critical in this analysis (lack of data).

Assumption 6: The energy intensity of commercial buildings, as well as the breakdown in electricity consumption for thermal and non-thermal purposes, is assumed to be constant.

Assumption 7: Both electricity and fuel prices are constant (future prices are very uncertain, so this helps simplify the calculations).

Assumption 8: The most dominant operating cost saving is fuel, not increased productivity, reduced maintenance, nor peak demand charges (these additional elements are difficult to estimate).

2.7 INTEGRATION

The complete Project Drawdown integration documentation (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 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[8]; adoptions are generally assumed independent for this. 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

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

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

In addition to building sector integration, there is an integration process across the grid and electricity efficiency solutions (buildings, transport, materials etc.) which adjusts for double counting. Double counting of emissions reduction was due to the use of 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[9]). Grid solutions are adjusted to account for double counting as described in the Project Drawdown integration documentation.

2.8 Limitations / Further Development

Despite the fact that commercial BAS is, in some form or another, relatively common in buildings, especially larger buildings, there have been very few actual analyses of the potential market for commercial building automation and controls and the potential they hold for reducing energy consumption and emissions from the global building stock. This report attempts to model the adoption of BAS globally and to calculate the climate and financial benefits of this adoption, but a number of key assumptions are necessary to simplify the calculations needed in modeling global-level adoption. Acknowledging that many of these assumptions do not perfectly mirror reality, the research team considered them necessary for the purposes of modeling at such a large scale.

There are some significant limitations to quantifying the benefits of adopting a suite of technologies (all bundled together under the term "BAS"). Principally, the top-down approach taken in this analysis does not allow for a very granular calculation of the costs and benefits of BAS adoption. For most building owners, making the decision to install a BAS is based on a very in-depth analysis of building function and savings estimates for the individual building or group of buildings. Even these estimates can have varying degrees of accuracy, so, when scaling up the level modeled to that of the global commercial building sector, these inaccuracies become multiplied.

The main approach taken in this model and report has been to conduct a detailed analysis of existing data where possible, but, for some aspects of the model, data limitations prohibited any detailed analysis. For

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

this reason, areas where robust data was available, such as for energy consumption and savings potentials, a more detailed analysis is undertaken. For model areas where data was limited, especially for adoption and capital costs, less time was spent in analysis, and instead, key assumptions were made to model these inputs.

This section briefly explains some of the main limitations of the modeling methodology and areas needing further improvement.

2.8.1 TAM and Adoption

Significant data limitations have hampered efforts to determine the current and future adoption of BAS. For this reason, broad and generalized assumptions were made, but this is a limitation that could be expanded on with more detailed data. Additionally, regional-level adoption was not prognosticated due to, again, the lack of reliable data, but a more customized approach to modeling regional adoption of BAS might enable a more accurate projection of adoption globally.

2.8.2 Climate and Financial Analyses

The primary limitation to these sections of the model is the lack of reliable data on costs for BAS and, specifically, the difference in costs for newer, advanced BAS compared to conventional technologies. Because of this, the entire first cost for the conventional technology in the model is predicated on a simple factoring calculation and an assumption that this factor is applicable to the full system. This is likely not an accurate calculation, but this was one way to model the first cost for conventional technologies based on existing data.

The rough estimates for energy intensity of commercial buildings also need improvement. Commercial buildings vary *significantly* in terms of their energy intensity but, because of the top-down approach taken, it was not possible to account for all the differences in energy use intensities in different types of commercial buildings.

2.8.3 Other Areas of Improvement

There are several other areas that need improvement. One is the modeling of the total financial benefits of BAS, taking into account additional factors such as: increased workplace productivity, reduced maintenance costs, and the reduction in commercial peak demand charges. This last area is one that might yield significant financial and climate benefits in commercial buildings that adopt an advanced BAS, but an estimate of these savings was not contained in this analysis. A comprehensive analysis of different automation technologies and the potential contributions they can make toward peak demand reduction in commercial buildings can be found in Roth et al. (2005).

The other area in need of improvement is related to BAS performance. Currently, the model does not estimate any ongoing maintenance or "commissioning" costs to ensure the BAS is operating efficiently and effectively, but this is a substantial component of most discussions of BAS implementation. Commissioning or continuous commissioning has significant potential for energy savings in commercial buildings and, in many buildings with a BAS, these are almost a necessity for energy savings to be realized. Additionally, this model does not consider the costs or benefits of automated fault diagnostic and detection (AFDD); this is another practice that is common within BAS and can lead to large energy savings (as well as a reduction in maintenance costs) (Roth et al, 2005).

Neither of these approaches common within the BAS literature were considered in this analysis. As BAS gain more traction within the commercial building sector, it is likely that much more data will be generated on the costs and benefits of different automation and control approaches, and there is no doubt that more robust and reliable data would improve this analysis.

3 RESULTS

Using the approach explained in the Methodology Section, three PDS scenarios for BAS adoption are constructed. These scenarios are summarized for each key output variable below.

3.1 ADOPTION

Below are shown the adoptions of the solution in some key years of analysis in functional units (million m^2 of commercial floor space) and percent.

Table 3.1 Global Adoption

	Units	Base Year (2014)	World Adoption by 2050		
			Plausible	Drawdown	Optimum
Building Automation Systems	Million m^2 Commercial Floor Space	16,578	51,953	69,538	88,291
	Percent of Market	57.2%	46.4%	62.0%	78.8%

The reduction in global adoption marketshare might be seen in the Plausible scenario since the individual regions have all grown in adoption, but some regions, most notably Asia sans Japan, started with very low adoption and are projected to explode in total floor area. As a result, the global adoption in percent terms is lower despite a large growth in area adopted.

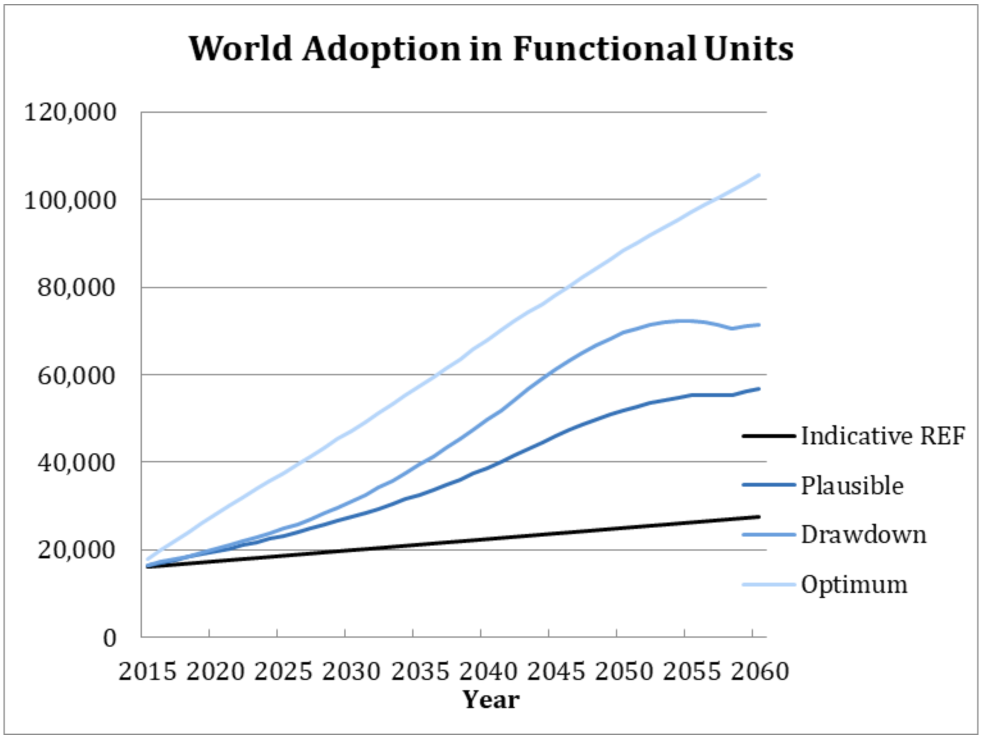

Figure 3.1 Global Annual Adoption 2015-2060

3.2 Climate Impacts

Below are the emissions results of the analysis for each scenario which include total emissions reduction and atmospheric concentration changes. For a detailed explanation of each result, please see the glossary. Because advanced BAS can substantially reduce energy consumption in commercial buildings, the climate impacts of PDS BAS adoption are significant. From 2020-2050, as the rate of adoption increases, the total reduction in emissions also accelerates. Table 3.2 *and* Table 3.3 present the climate results from the PDS scenario.

Table 3.2 Climate Impacts

Scenario	Maximum Annual Emissions Reduction	Total Atmospheric CO2-eq Reduction	Emissions Reduction in 2030	Emissions Reduction in 2050
	(Gt CO2-eq/yr.)	*Gt CO2-eq (2020-2050)*	*(Gt CO2-eq/year)*	*(Gt CO2-eq/year)*
Plausible	0.39	6.02	0.12	0.39
Drawdown	0.64	9.56	0.17	0.64

Scenario	Maximum Annual Emissions Reduction	Total Atmospheric CO2-eq Reduction	Emissions Reduction in 2030	Emissions Reduction in 2050
	(Gt CO2-eq/yr.)	*Gt CO2-eq (2020-2050)*	*(Gt CO2-eq/year)*	*(Gt CO2-eq/year)*
Optimum	0.87	16.37	0.41	0.87

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 CO2-eq (2050)	*PPM CO2-eq change from 2049-2050*
Plausible	0.51	0.03
Drawdown	0.82	0.05
Optimum	1.35	0.07

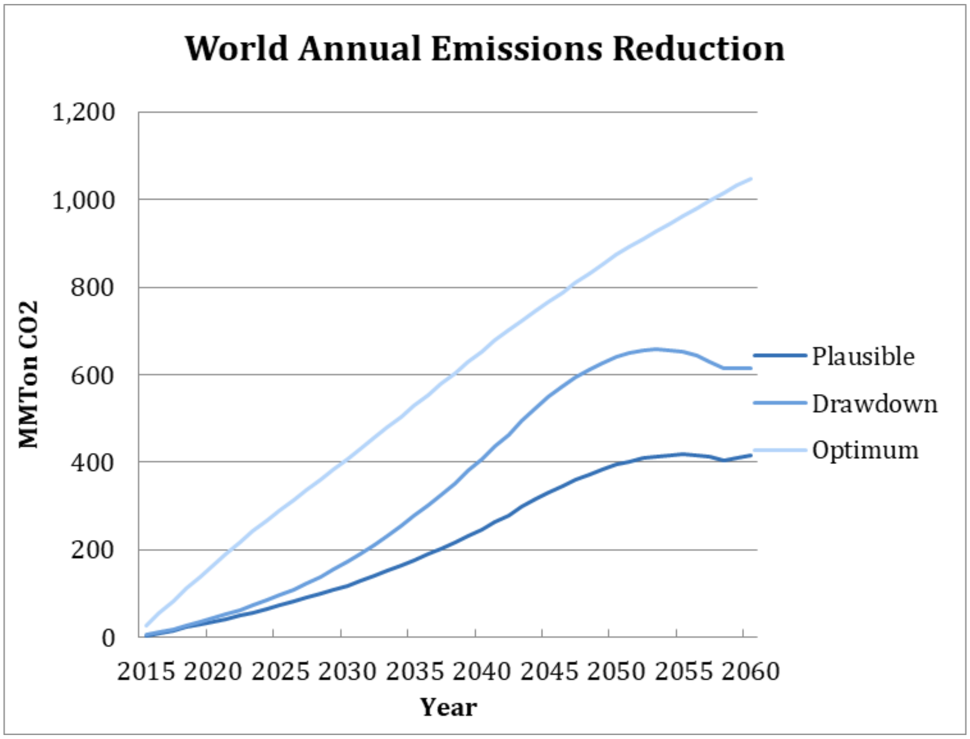

Figure 3.2 World Annual Greenhouse Gas Emissions Reduction Compared to REF

3.3 FINANCIAL IMPACTS

Below, in Table 3.4, are the financial results of the analysis for each scenario. For a detailed explanation of each result, please see the glossary. Some operating results are illustrated in Figure 3.3.

Table 3.4 Financial Impacts

Scenario	Cumulative First Cost	Marginal First Cost	Net Operating Savings	Lifetime Operating Savings	Lifetime Cashflow Savings NPV (of All Implementation Units)
	2015-2050 Billion USD	*2015-2050 Billion USD*	*2020-2050 Billion USD*	*2020-2050 Billion USD*	*Billion USD*
Plausible	960.23	164.22	1,054.40	1,696.06	123.96
Drawdown	1,354.04	238.72	1,679.28	2,699.13	186.23
Optimum	2,006.27	403.82	2,839.63	4,243.46	385.59

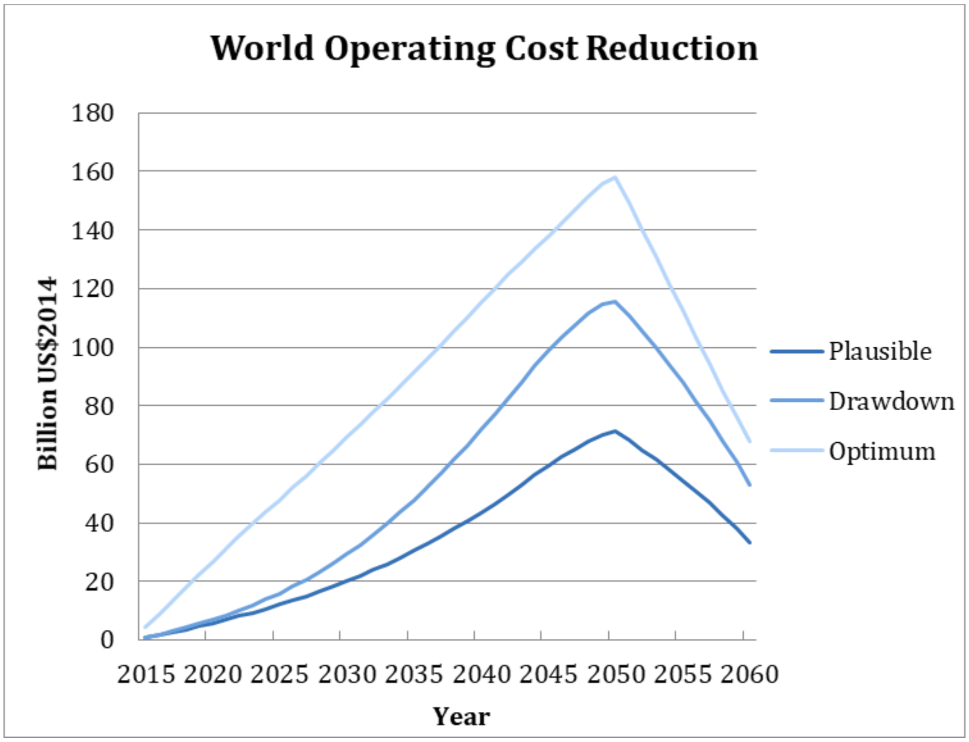

Figure 3.3 Operating Cost Reduction Over Time Under Each Scenario

These results show that rapid global adoption of BAS by 2050 can contribute significantly to carbon emissions reductions while also yielding significant savings from reduced energy expenditures within commercial buildings. These results also do not consider a number of other "add-on" savings that could be realized from BAS adoption, including large gains in worker productivity and operation efficiencies. Adding these benefits to the results make this solution an even more attractive one for reducing emissions from the building sector.

4 Discussion

BAS is a growing area of interest among different stakeholders, ranging from building managers to global agencies, due to their potential to reduce energy consumption and building emissions while improving occupant comfort, workplace productivity, and building operations. Implementing BAS technologies in commercial buildings can contribute significantly to global emissions reductions, especially from a sector that has historically been a high emitter of CO_2. As wireless sensor technologies and integrated network systems continue to grow in popularity, BAS will play an increasing role in reducing energy consumption in commercial buildings. A number of trends and drivers can encourage rapid adoption, including broad efforts to ensure all buildings by 2050 have net-zero emissions.

Current adoption for BAS is predominantly concentrated in the U.S., EU, and in China. Future growth will occur primarily in these regions, but a number of countries and regions, such as Japan, Brazil, and several countries in the Middle East will also see increased growth in the coming decades. While this model has used high-level estimates of the savings potential of BAS technologies in commercial buildings, there are clearly significant savings to be realized in these buildings through installing advanced control technologies that can communicate, integrate, and make building processes more intelligent.

The high-tech, clean energy economy of the future will rely on smart, interconnected buildings that can adjust and adapt their function and operation based on large volumes of data. A centralized system that can interpret and react to this data is essential for developing these intelligent buildings in future urban and suburban areas. Because of their savings potential and many additional benefits, BAS is an important solution for reducing energy consumption from the building sector and, thus, they are essential for *Drawdown.*

4.1 Limitations

BAS represent a no-regret solution for global emissions reductions because of their substantial net savings, their ability to improve workplaces and building operations, and their flexibility in terms of design and application. Although BAS have their own disadvantages, many of these barriers can be overcome, and they will likely pose less of a hindrance to BAS growth as the costs for these systems decline and the technologies used in BAS become more integrated and intuitive.

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6 GLOSSARY

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

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

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

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

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**.

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.

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