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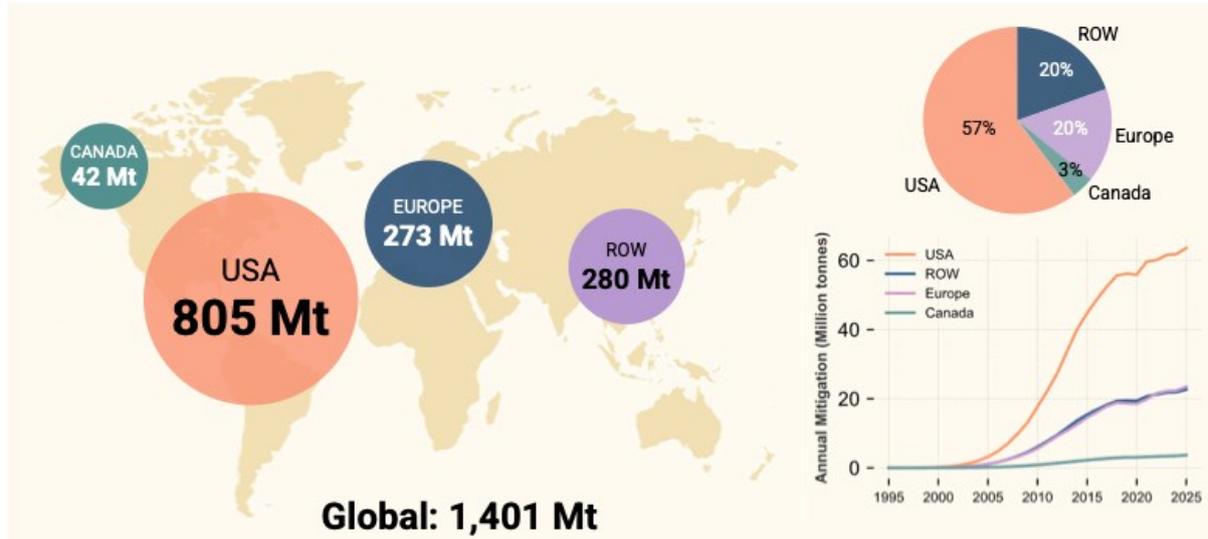
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# Global Carbon Mitigation from BACnet Adoption in Commercial Building Automation Systems 1995-2030

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## ABSTRACT



Building Automation Systems (BAS) play a critical role in improving energy efficiency in commercial buildings, yet their long-term carbon mitigation potential has not been comprehensively quantified at a global scale. As the dominant open communication standard enabling interoperability in modern BAS, BACnet has played a central role in expanding automation adoption worldwide. This study develops a cohort-based modeling framework to estimate historical (1995–2025) and projected (2026–2030) CO<sub>2e</sub> mitigation from BACnet-based BAS adoption across four regions: the United States, Canada, Europe, and the Rest of World (ROW). The model combines regional commercial floor area, baseline electricity and natural-gas energy intensity, BAS adoption rates, electricity carbon-intensity trajectories, and system performance decay to produce annual and cumulative mitigation estimates. Results show that BAS have avoided approximately 1,401 million tonnes of CO<sub>2e</sub> globally from 1995–2025 and are projected to reach 2,065 million tonnes by 2030. The carbon reduction achieved so far is roughly equal to the annual emission of the entire Japan – the world’s fifth largest emitter, or removing 300 million cars from the road for an entire year. Annual mitigation increases over time due to the accumulation of overlapping BAS cohorts but slows after the mid-2010s as adoption growth levels off and electricity grids decarbonize. Significant regional differences emerge: electricity dominates mitigation in the United States (~70%), while natural gas plays an equally important or larger role in Europe and Canada due to colder climates and gas-intensive heating loads. Cohort-level analysis shows clear performance decay and reduced post-replacement peaks, driven by declining electricity carbon intensity. These findings demonstrate that BAS deliver robust and persistent energy savings, but the carbon value of those savings depends increasingly on regional grid decarbonization pathways. The results highlight the continued importance of BAS, supported by BACnet interoperability, as a near-term mitigation strategy and underscore the need for sustained maintenance and broader deployment in under-automated building segments.

## 1 INTRODUCTION

Commercial buildings account for a significant share of global energy consumption and carbon emissions, driven by heating, cooling, lighting, ventilation, and plug loads. According to the International Energy Agency (IEA), buildings contribute roughly 30% of global energy consumption and 26% of energy-related carbon emissions [1]. Improving operational efficiency in this sector is therefore essential for meeting national and international decarbonization targets. Among available strategies, Building Automation Systems (BAS), including HVAC controls, scheduling, ventilation optimization, and sensor-driven operation, are widely recognized as one of the most cost-effective pathways in the near term.

A key enabler of modern BAS adoption has been BACnet [2], the open, internationally recognized communication protocol specifically designed for building control systems. Introduced by ASHRAE (The American Society of Heating, Refrigerating and Air-Conditioning Engineers) in the 1990s, first published by ISO (International Organization for Standardization) as ISO 16484-5 in 2003 and now adopted in more than 190 countries, BACnet ensures interoperability among devices from different manufacturers, reducing integration costs and enabling large-scale deployment of automated building controls. The expansion of BAS worldwide has closely mirrored the maturation and global adoption of BACnet.

BACnet-based BAS enable dynamic, real-time control of building systems and have demonstrated substantial capability to reduce energy consumption. A landmark study by Pacific Northwest National Laboratory (PNNL) found that implementing properly tuned, modern control strategies can reduce commercial-building energy use by approximately 29%, based on field studies across numerous U.S. building types [3]. Similar results have been observed internationally, with studies in Europe reporting 15–30% savings depending on building type, climate, and automation sophistication [4,5]. BACnet’s open architecture has been instrumental in scaling these benefits by allowing multi-vendor systems to communicate seamlessly, reducing integration costs, and accelerating deployment across diverse building portfolios.

Despite the recognized value of BAS for reducing energy use, their carbon-mitigation potential over the long-term horizons, considering the dynamic adoption and replacement patterns, remains under studied. Most prior analyses focus on short-term savings at the building level, whereas the climate impact of BAS depends on long-term adoption trends, regional electricity and gas intensities, lifetime performance decay, and changing electricity carbon intensity. Moreover, differences across regions, such as heating-dominated climates in Canada and parts of Europe, mean that reductions in direct natural gas use for space and water heating may deliver as much or more carbon benefits as electricity savings, especially where electricity grids are already low carbon.

To address this gap, this study develops a cohort-based global assessment of CO<sub>2</sub> mitigation from BACnet-based BAS adoption in commercial buildings from 1995–2030 across the United States, Canada, Europe, and the Rest of World (ROW). The analysis integrates regional floor-area growth, energy-use intensities, automation adoption rates, carbon-intensity trajectories, and BAS persistence behavior to quantify both historical and near-future mitigation. By capturing cohort aging, replacement cycles, and evolving grid decarbonization, the study provides the first unified global estimate of BAS-driven carbon mitigation and clarifies how the climate benefits of BAS will evolve as energy systems transition.

## 2 METHODOLOGY

This study quantifies the historical (1995-2025) and projected (2026-2030) carbon mitigation attributable to building automation systems (BAS) using the BACnet

communication standard. The analysis follows a fully modular, fuel-specific, cohort-based modeling approach developed for this project. It estimates annual and cumulative carbon mitigation from 1995 through 2030 across four regions: the United States, Canada, Europe, and the Rest of the World (ROW). Figure 1 shows the overarching analysis pipeline used to estimate the carbon mitigation from BAS-enabled commercial buildings.

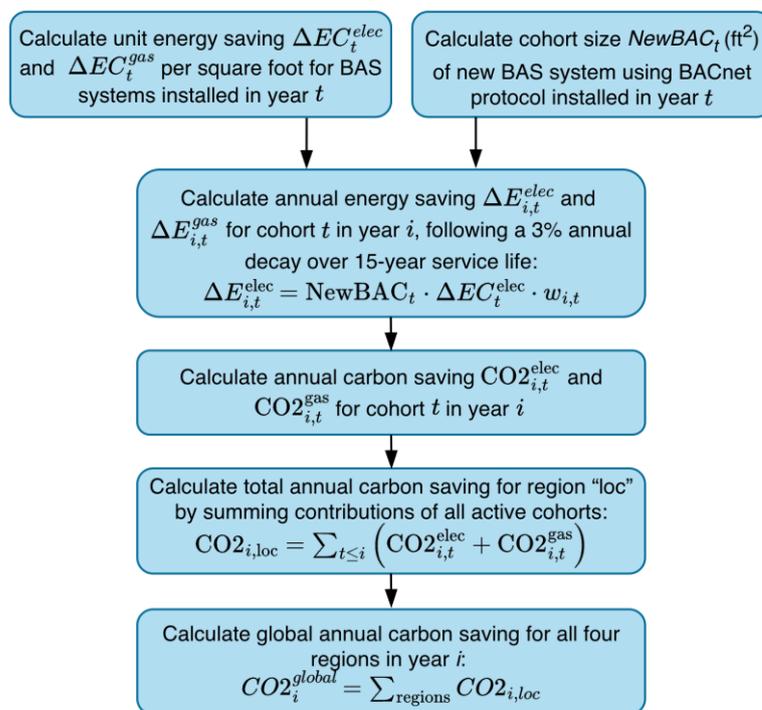


Figure 1 Analysis pipeline for estimating carbon mitigation from BAS-enabled commercial buildings

Table 1 Definition for variables used in this analysis

Variable	Definition & Units
$A_t$	Total commercial building floor area in year $t$ (ft <sup>2</sup> ).
$r_t$	BAS automation adoption rate — fraction of building stock with BAS in year $t$ (unitless, 0–1).
$b_t$	BACnet adoption rate among new BAS installations in year $t$ (unitless, 0–1).
$EC_t$	Overall energy-consumption intensity for year $t$ (kWh/ft <sup>2</sup> for electricity; ft <sup>3</sup> /ft <sup>2</sup> for natural gas).
$naEC_t$	Inferred non-automated energy-consumption intensity (same units as $EC_t$ ).
$s$	BAS energy-savings fraction (unitless; assumed to be 22.5% in this study).
$\Delta EC_t$	Per-square-foot energy-intensity gap for new BAS installations in year $t$ (same units as $EC_t$ ).
$BAS\_stock_t$	BAS-enabled commercial floor area in year $t$ (ft <sup>2</sup> ).
$NewBAS_t$	Newly added BAS-enabled floor area in year $t$ (ft <sup>2</sup> ).
$NewBAC_t$	Newly added BACnet-enabled BAS floor area (cohort size) in year $t$ (ft <sup>2</sup> ).

$L$	BAS system lifetime before replacement (years). (assumed to be 15 years in this study)
$d$	Annual BAS performance decay rate (unitless; e.g., 0.03).
$w_{i,t}$	Operational weight for cohort installed in year $t$ and evaluated in year $i$ (unitless).
$\Delta E_{i,t}^{elec}$	Annual electricity savings from the cohort installed in year $t$ , evaluated in year $i$ (kWh/yr).
$\Delta E_{i,t}^{gas}$	Annual natural gas savings from the cohort installed in year $t$ , evaluated in year $i$ (ft <sup>3</sup> /yr).
$CI_t^{elec}$	Electricity carbon intensity for year $i$ (tonnes CO <sub>2e</sub> per kWh).
$CI_t^{gas}$	Natural-gas carbon intensity for year $i$ (tonnes CO <sub>2e</sub> per ft <sup>3</sup> or tonnes CO <sub>2e</sub> per kWh-eq).
$CO2_{i,t}^{elect}$	Carbon mitigation from electricity savings for cohort $t$ in year $i$ (tonnes CO <sub>2e</sub> /yr).
$CO2_{i,t}^{gas}$	Carbon mitigation from natural-gas savings for cohort $t$ in year $i$ (tonnes CO <sub>2e</sub> /yr).
$CO2_{i,t}$	Total carbon mitigation from cohort $t$ in year $i$ (tonnes CO <sub>2e</sub> /yr).
$CO2_{i,loc}$	Total carbon mitigation from all active cohorts for region “loc” in year $i$ (tonnes CO <sub>2e</sub> /yr).
$CO2_i^{global}$	Total global carbon mitigation in year $i$ , summed across all regions (tonnes CO <sub>2e</sub> /yr).

## 2.1. Energy Intensities for automated and non-automated systems

For each region and year  $t$ , we gathered data on the observed overall energy-consumption rate  $EC_t$ , measured in kWh/ft<sup>2</sup> for electricity and ft<sup>3</sup>/ft<sup>2</sup> for natural gas. This overall intensity reflects commercial buildings both with and without building automation systems (BAS). We assume that a BAS-enabled building reduces energy use by a savings fraction  $s = 22.5\%$ , meaning that buildings with BAS consumes 22.5% less energy per unit floor area than non-BAS buildings. Knowing the adoption rate  $r_t$  for BAS in year  $t$ , we can estimate the non-automated building’s energy consumption rate:

$$naEC_t = \frac{EC_t}{1 - s r_t} \quad \text{Eq. 1}$$

The **per-square-foot energy-intensity gap** (savings potential) for a BAS installation occurring in year  $t$  is:

$$\Delta EC_t = s \cdot naEC_t = \frac{s EC_t}{1 - s r_t} \quad \text{Eq. 2}$$

This inferred energy-intensity gap  $\Delta EC_t$  is fixed for all BAS floor area installed in year  $t$ . Each cohort formed in that year uses the same value of  $\Delta EC_t$  when calculating energy savings in subsequent years throughout its lifetime. When the cohort reaches the end of its 15-year life and is replaced, the replacement cohort adopts the updated energy-intensity gap for the replacement year, ensuring that savings reflect the prevailing energy-use conditions at the time of replacement. This per-square-foot energy-intensity gap is calculated for both electricity and natural gas, resulting in  $\Delta EC_t^{elec}$  (kWh/ft<sup>2</sup>) and  $\Delta EC_t^{gas}$  (ft<sup>3</sup>/ft<sup>2</sup>), respectively.

## 2.2. Cohort Formation and New BAS Installations

For each region and year  $t$ , we estimate how much commercial floor area receives a **new installation** of a BACnet-enabled building automation system (BAS). This is achieved by tracking the portion of the building stock that is already automated and identifying the incremental increase in BAS penetration over time. Let  $A_t$  denote the total commercial building floor area in year  $t$ , and  $r_t$  be the automation adoption rate—the fraction of the existing stock that has BAS installed. The total BAS-equipped floor area in year  $t$  is therefore:

$$BAS\_stock_t = A_t r_t \quad \text{Eq. 3}$$

The increment in BAS-equipped area from the previous year  $t-1$  to year  $t$  represents the **new BAS installations**  $NewBAS_t$  (ft<sup>2</sup>) for year  $t$ . Because we only count new installations, negative changes are set to zero:

$$NewBAS_t = \max(BAS\_stock_t - BAS\_stock_{t-1}, 0) \quad \text{Eq. 4}$$

Not all new BAS installations use the BACnet protocol. Let  $b_t$  represent the BACnet adoption fraction for new BAS projects in year  $t$ . The resulting **new BACnet-enabled area** (ft<sup>2</sup>) added in year  $t$  is:

$$NewBAC_t = NewBAS_t b_t \quad \text{Eq. 5}$$

This  $NewBAC_t$  value defines the cohort size of newly installed BAS-enabled building area using the BACnet protocol in year  $t$ . Each cohort is tracked independently in later years to compute energy savings, performance decay, and eventual system replacement. In this framework, every year  $t$  generates a new cohort reflecting the incremental expansion of BACnet-enabled automation across the commercial building sector.

## 2.3. Cohort Annual Carbon Saving

Once a cohort of BACnet-enabled BAS installations is established in year  $t$ , its contribution to energy savings and carbon mitigation evolves over time. Each cohort produces annual savings for up to 15 years, after which the system is replaced and the cohort is renewed.

**Annual Energy Savings for Each Cohort:** For the BAS-enabled floor area  $NewBAC_t$  installed in year  $t$ , the annual energy savings generated by this cohort from electricity usage in a later calendar year  $i$  ( $i \geq t$ ) is:

$$\Delta E_{i,t}^{elec} = NewBAC_t \cdot \Delta EC_t^{elec} \cdot w_{i,t} \quad \text{Eq. 6}$$

where  $w_{i,t}$  is an operational weight that accounts for the cohort's age and whether the installation represents a brand-new system or a replacement system. Similarly, we calculate the annual energy saving from natural gas for each cohort  $t$ :

$$\Delta E_{i,t}^{gas} = NewBAC_t \cdot \Delta EC_t^{gas} \cdot w_{i,t} \quad \text{Eq. 7}$$

**Performance Decay and replacement:** BAS performance gradually declines due to operational drift, sensor degradation, and maintenance-related factors. We model this effect

using a constant annual decay rate  $d = 3\%$ , with a corresponding persistence factor  $p = 1 - d$ . Each cohort operates for a lifetime of  $L = 15$  years. At year  $t + L$ , the cohort is replaced by a new system of the same floor area:  $NewBAC_{t+L} = NewBAC_t$ . This replacement is treated as a new cohort installed in year  $t + L$ , adopting the updated energy-intensity gap  $\Delta EC_{t+L}$  based on prevailing conditions in that year. After replacement, the installation year for this cohort becomes  $t \leftarrow t + L$ , and subsequent calculations follow the same rules for annual savings, performance decay, and eventual replacement.

**Operational Weight:** For a cohort installed or replaced in year  $t$ , its age in year  $i$  is  $i - t$ . The operational weight for brand-new installations is:

$$w_{i,t} = \begin{cases} 0.5, & i = t, \text{ and the cohort is a new installation,} \\ 1, & i = t, \text{ and the cohort is a replacement installation,} \\ p^{(i-t)}, & k > t, \text{ and } (k - t) < L. \end{cases} \quad \text{Eq. 8}$$

where the half-year weight (=0.5) for  $i = t$  reflects the fact that newly installed BAS systems operate for only a portion of their installation year, whereas replacements are assumed to operate effectively for the full year. After the installation year, both new and replacement cohorts follow the same decay pattern  $p^{(i-t)}$  until they reach their 15-year lifetime and are replaced.

#### 2.4. Carbon Conversion: Translating Energy Savings into CO<sub>2</sub> Reductions

The annual energy savings produced by each cohort are converted into carbon mitigation using region-specific carbon-intensity factors. Because electricity and natural gas have different emission characteristics, the model computes carbon impacts separately for each fuel type and then sums the results.

**Carbon Intensity for Electricity and Natural Gas:** To translate energy savings into avoided carbon emissions, we apply fuel-specific carbon-intensity factors. For electricity, the carbon intensity  $CI_i^{elec}$  represents the amount of carbon emitted per unit of electricity consumption in year  $i$  and is expressed in tonnes of CO<sub>2</sub>e per kWh. For natural gas, the carbon intensity  $CI_i^{gas}$  reflects the carbon emitted per unit of gas use in year  $i$ , typically expressed in tonnes of CO<sub>2</sub>e per cubic foot.

**Regional Annual Carbon Mitigation:** Given the annual energy savings  $\Delta E_{i,t}$  for a cohort installed in year  $t$ , the corresponding carbon mitigation from electricity in year  $i$  is:

$$CO2_{i,t}^{elec} = \Delta E_{i,t}^{elec} \cdot CI_i^{elec} \quad \text{Eq. 9}$$

and from natural gas:

$$CO2_{i,t}^{gas} = \Delta E_{i,t}^{gas} \cdot CI_i^{gas} \quad \text{Eq. 10}$$

It is important to note that carbon-intensity factors are applied using the values for the year in which the savings occur, not the installation year. This ensures that annual carbon mitigation

accurately reflects evolving electricity-grid decarbonization and fuel-mix changes over time. The total carbon mitigation from this cohort in year  $i$  is the sum of electricity and natural gas contributions:

$$CO2_{i,t} = CO2_{i,t}^{elec} + CO2_{i,t}^{gas} \quad \text{Eq. 11}$$

The total annual carbon mitigation for region “loc” in calendar year  $i$  is obtained by summing the contributions of all active cohorts:

$$CO2_{i,loc} = \sum_{t \leq i} CO2_{i,t} \quad \text{Eq. 12}$$

$$CO2_{i,loc} = \sum_{t \leq i} CO2_{i,t}^{elec} + CO2_{i,t}^{gas}$$

where the summation only includes cohorts with ages less than the 15-year lifetime because older cohorts have already been replaced by new ones. Finally, the global annual carbon mitigation for year  $i$  is computed by summing across all regions:

$$CO2_i^{global} = \sum_{\text{regions}} CO2_{i,loc} \quad \text{Eq. 13}$$

### 3 DATA

The model integrates annual commercial building floor area, baseline energy use, BAS and BACnet adoption rates, and carbon-intensity data across the United States, Canada, and Europe. Table 2 summarizes the sources, assumptions and processing methods for the data used in the assessment of carbon mitigation due to building automation system adoptions.

Table 2 Summary of Data Inputs Used in the BAS Carbon-Mitigation Assessment

Data Type	Primary Sources	Processing Steps	Key Assumptions / Notes
Commercial Building Floor Area $A_t$	- USA: EIA CBECS [6] - Canada: NRCan SCIEU [7], National Energy Use Handbook [8] - Europe: European Building Stock Observatory (EEA) [9], BPIE [10]	- Extract annual values - Regression using linear function (USA and Europe) or polynomials (Canada) for missing years	- Represents total commercial floor area
Electricity Baseline EC (kWh/ft <sup>2</sup> )	- USA: EIA CBECS [6] - Canada: NRCan SCIEU [7], National Energy Use Handbook [8] - Europe: European Building Stock Observatory (EEA) [9], BPIE [10]	- Extract annual values - Linear Regression (for Canada and USA) and bilinear fitting (for Europe) for missing years	- EIA CBECS data are available for 1995, 1999, 2003, 2012, and 2018.
Natural Gas Baseline EC (ft <sup>3</sup> /ft <sup>2</sup> )	- USA: EIA CBECS [6] - Canada: NRCan SCIEU [7], National Energy Use Handbook [8] - Europe: BPIE [10]	- Extract annual values - Linear Regression (for Canada and USA) for missing years	- Europe: assume that 35% of the commercial building energy consumption (275 kWh/m <sup>2</sup> ) is from natural gas; then converted to ft <sup>3</sup> of gas using 38 MJ/m <sup>3</sup> .
Electricity Carbon Intensity (tCO <sub>2e</sub> /kWh)	- USA: EIA Monthly Energy Review (MER) [11] - Canada: national inventory report [12] - Europe: EEA [13]	- Extract annual values - Convert to consistent units - Interpretation for missing years	- Data is relatively complete.
Natural Gas Carbon Intensity (tCO <sub>2e</sub> /ft <sup>3</sup> )	- USA: EIA Carbon Dioxide Emissions Coefficients [14] - Canada: Emission Factors and Reference Values [15] - Europe: IPCC [16]	- Convert to consistent units	- Natural gas carbon intensities were assumed constant for each region since they remain stable over the years.

Commercial floor area and baseline electricity use were sourced from EIA CBECS (USA) [6], NRCan SCIEU [7] and National Energy Use data (Canada) [8], and the European Building Stock Observatory and BPIE (Europe) [9,10]. Because these datasets are reported at irregular intervals, annual values from 1995–2030 were constructed using linear or quadratic regression. Baseline electricity and natural-gas energy intensities represent the mixed building stock (automated and non-automated buildings combined). To estimate the energy-savings potential for new BAS installations, the model reconstructs the non-automated energy intensity using the automation adoption rate and the assumed BAS savings fraction (detailed in the Methodology section).

Natural gas data required an additional assumption for Europe, where no consistent time series exists for commercial natural-gas consumption. We assumed that approximately 35% of non-residential energy use ( $\approx 275$  kWh/m<sup>2</sup> per year, based on BPIE [10]) is from natural gas and converted this value to ft<sup>3</sup>/ft<sup>2</sup> using a typical heating value of 38 MJ/m<sup>3</sup>. This yields an annual natural gas consumption rate of 30 ft<sup>3</sup>/ft<sup>2</sup>, which is consistent with European commercial gas-use benchmarks. Sensitivity checks confirm that uncertainty in this assumption has a relatively small impact on overall mitigation results.

Annual electricity carbon-intensity data were obtained from authoritative, region-specific sources: the EIA Monthly Energy Review (USA) [11], Canada’s National Inventory Report (NRCan) [12], and European Environment Agency (EEA) data [13]. Because electricity carbon intensity (CI) changes significantly over time due to decarbonization, these annual trends are preserved in the model, with data shown in Figure 2. In contrast, natural-gas carbon intensity was assumed constant over 1995–2030 for each region being considered. This

constant-CI assumption is standard in national GHG inventories and appropriate for modeling on-site combustion emission [16].

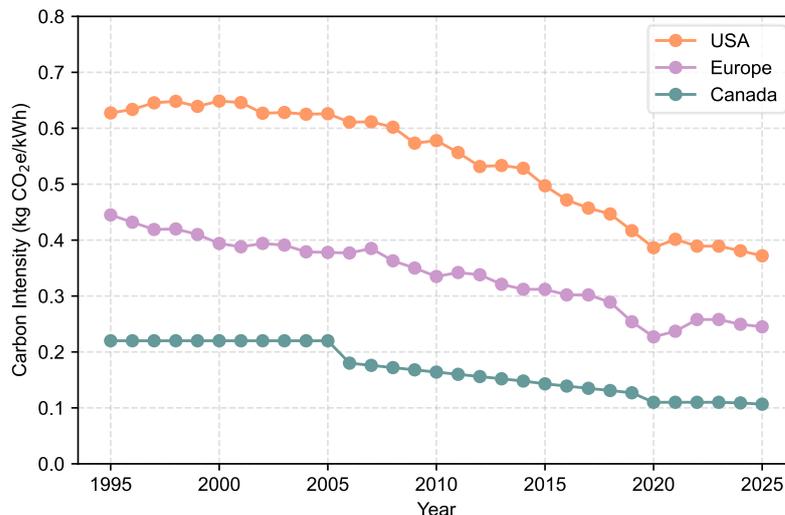


Figure 2 Electricity carbon intensity trends (kg CO<sub>2</sub>e/kWh) for the United States, Europe, and Canada from 1995 to 2025, showing long-term grid decarbonization patterns and regional variation relevant to BAS energy-emissions modeling.

Finally, the model applies two key performance assumptions: a 22.5% BAS savings fraction (based on meta-analysis of BAS performance studies [3,17]) and a 3% annual system efficiency degradation rate, which reflects typical declines in BAS effectiveness due to calibration drift and operational override. These assumptions ensure that results remain conservative and consistent with observed BAS performance in real commercial buildings.

## 4 RESULTS AND DISCUSSIONS

This section presents estimates of historical (1995–2025) and projected (2026–2030) CO<sub>2</sub> mitigation attributable to BACnet-based building automation systems (BAS) in commercial buildings across four global regions: the United States, Canada, Europe, and the Rest of World (ROW). Mitigation results are disaggregated by energy source (electricity and natural gas), region, and BAS installation cohort to reveal both aggregate trends and underlying system dynamics.

### 4.1. Regional mitigation potential

Table 2 summarizes cumulative CO<sub>2</sub> mitigation from electricity and natural gas across regions. Between 1995 and 2025, global BACnet-based BAS adoption avoided an estimated 1,401 million tonnes (Mt) of CO<sub>2</sub>, with the United States contributing the largest share (805 Mt), followed by Europe (273 Mt), ROW (280 Mt), and Canada (42 Mt). When projected adoption through 2030 is included, global cumulative mitigation reaches approximately 2,065 Mt CO<sub>2</sub>e.

Table 3 Carbon Mitigation by source and region (Unit: Million Tonnes of CO<sub>2</sub>e)

Period: 1995-2025					
Category	USA	Canada	Europe	ROW	Global
Electricity	602	15	160	194	972
Natural Gas	203	27	113	86	429

Electricity+Gas	805	42	273	280	1,401
Period: 2025-2030 Projection					
Category	USA	Canada	Europe	ROW	Global
Electricity Mitigation	251	8	69	82	410
Natural Gas Mitigation	113	15	77	51	256
Electricity+Gas	364	23	146	133	666

Figure 2a visualizes the distribution of these impacts across electricity and natural gas. Electricity savings dominate total mitigation in all regions, reflecting both higher electricity intensity in commercial buildings and the relatively high historical carbon intensity of electricity generation. Figure 2b further illustrates that mitigation is expected to accelerate through 2030, particularly in the United States and Europe, where BAS adoption in large commercial facilities continues to expand.

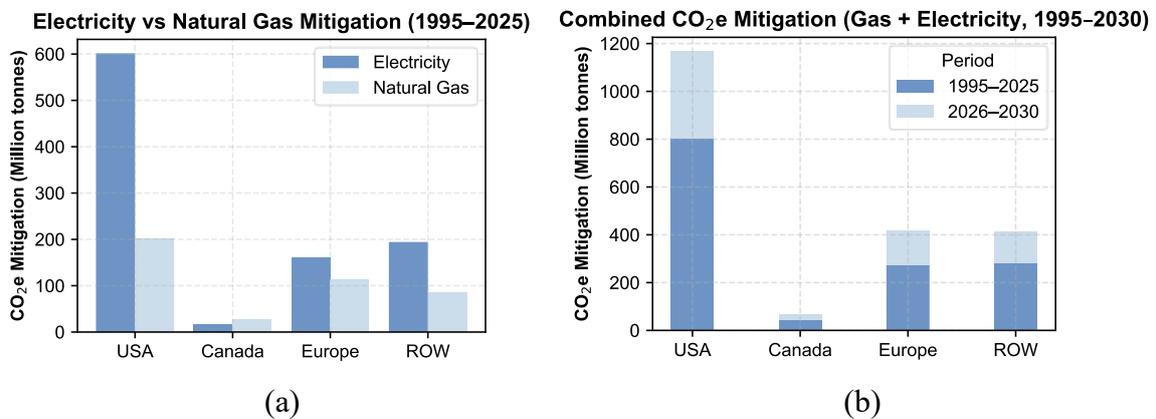


Figure 3 Comparison of estimated carbon Mitigation by source and region: (a) carbon mitigation from electricity and natural gas during 1995-2025; (b) total carbon mitigation (electricity + natural gas) in the four regions, including projected mitigation from 2026 to 2030

Across regions, differences in mitigation magnitude are driven by three interacting factors: (1) total commercial floor area, (2) historical BAS adoption rates, and (3) regional electricity carbon intensity. The United States leads by a wide margin due to its large commercial building stock and early, sustained BAS adoption. Europe exhibits strong growth beginning in the mid-2000s, consistent with the region’s regulatory emphasis on energy performance in buildings. Canada shows more modest contributions due to smaller commercial building stocks.

#### 4.2. Annual mitigation trends by energy source

Figure 4 illustrates annual carbon mitigation from BACnet-based BAS adoption across four global regions from 1995–2025. Annual mitigation increases consistently over this period because each new cohort of BAS installations adds to the existing stock of active BAS. With BAS operating over 15-year lifetimes, overlapping cohorts accumulate, producing a rising mitigation trend as adoption expands. This “stacking” effect is the primary driver of sustained growth in annual carbon savings. However, the rate of growth slows after about 2016–2017 in all regions. Two structural mechanisms explain this shift. First, BAS adoption in large commercial buildings begins to level off, reducing the size of new BAS cohorts entering service each year. Second, decarbonization of the electricity grid reduces the carbon intensity of

electricity consumption globally. The carbon mitigation corresponding to each kilowatt-hour of electricity saving reduces over time.

Distinct regional patterns reflect differences in energy use, climate, and fuel mix. In the United States, electricity accounts for roughly 70% of mitigation because commercial buildings have high electricity loads (cooling, lighting, plug loads) and historically higher electricity carbon intensity. In contrast, Europe shows comparable or even greater mitigation from natural gas, reflecting widespread reliance on gas-based space heating in colder climates and relatively lower electricity intensity per square foot. Canada displays the strongest gas-dominant behavior: long heating seasons and heavy use of natural-gas heating produce greater carbon mitigation from gas than electricity, especially given Canada’s already low-carbon electricity grid. These patterns highlight how BAS-driven mitigation is shaped not only by adoption trends but also by regional energy-system characteristics and long-term decarbonization pathways.

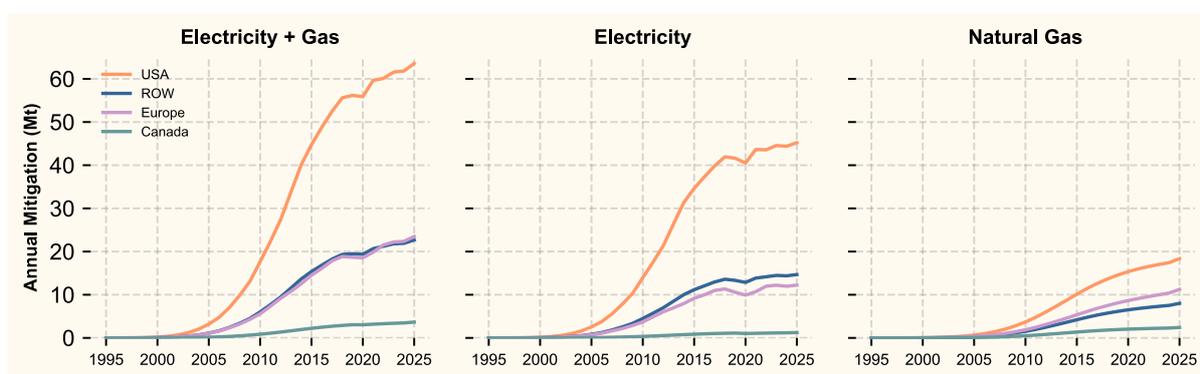


Figure 4 Annual carbon mitigation (million tonnes) by region during 1995–2025 from: (a) combined electricity + gas, (b) electricity, and (c) natural gas.

### 4.3. Cohort-level dynamics and the role of electricity carbon intensity

To better understand the temporal structure of BACnet-based BAS-driven mitigation, Figure 5 examines annual electricity-related carbon savings from individual BAS installation cohorts in the United States; other regions exhibit similar trends shown in the figure. Panel 4a compares six representative cohorts installed between 1995 and 2020, while panels 4b and 4c provide zoomed views of the earliest cohorts. Two consistent patterns emerge across all cohorts:

1. **Initial performance peak and gradual decay.** Because BAS installations occur throughout the year, our model applies a 50% weighting in the installation year, producing a half-sized first-year impact. The full peak appears in the following year, after which performance declines systematically. This behavior aligns with observed BAS performance degradation in real buildings, where sensor drift, overridden control sequences, deferred maintenance, and operational changes reduce achievable savings over time. This phenomenon is modeled as a 3% annual persistence decay.

2. **Recovery after replacement, but with reduced peak magnitude.** Each cohort is assumed to be replaced with a new BAS after a 15-year service life, recovering its full energy-saving capability. However, the resulting carbon mitigation peak is smaller than the original installation peak. This is driven by the decline in electricity carbon intensity over time (Figure 4d): as the grid decarbonizes, each kilowatt-hour saved corresponds to fewer avoided carbon emissions. Thus, even though post-replacement electricity savings remain comparable, the carbon benefit is reduced due to structural changes in the electricity system.

These cohort-level results highlight an important insight: BAS continue to deliver robust energy savings across multiple decades, but the climate benefit of these savings depends increasingly on regional grid decarbonization pathways. In regions with rapid electricity decarbonization, the carbon reduction potential from BAS electricity savings will gradually decline—even if automation effectiveness remains high. Conversely, improvements in natural-gas efficiency will remain valuable due to the stable carbon intensity of combustion-based heating.

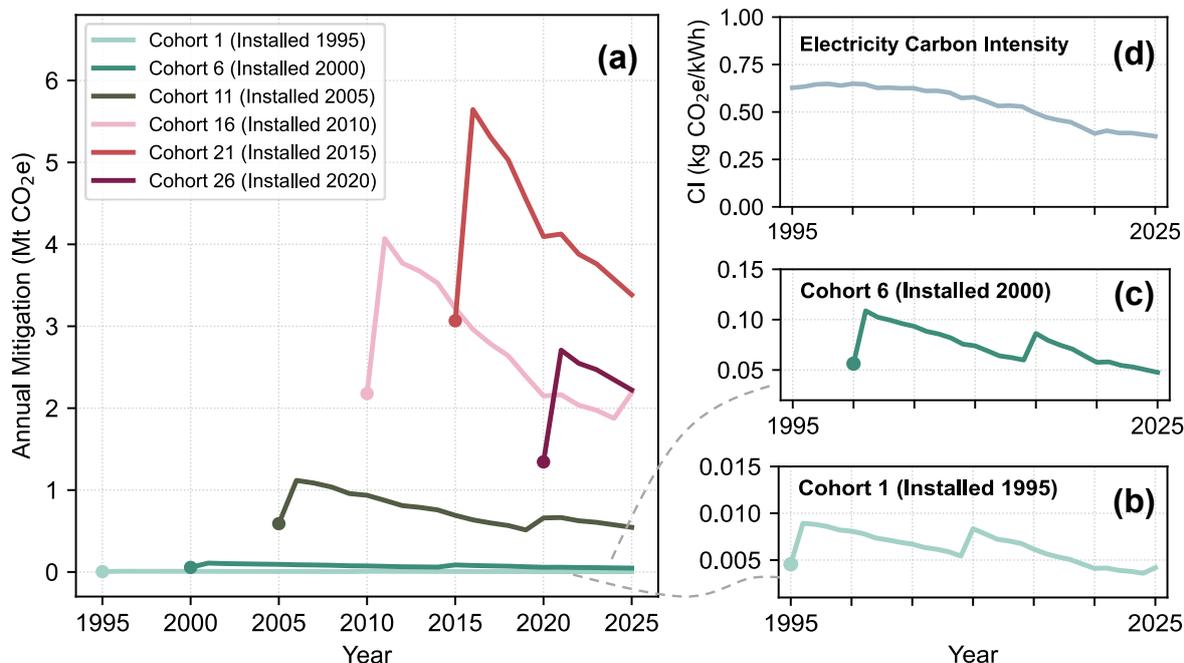


Figure 5 Annual carbon mitigation from electricity savings by representative building automation cohorts in United States: (a) Annual mitigation contributions from six representative installation cohorts (1995–2020), expressed in Mt CO<sub>2</sub>e per year; (b) Zoomed annual mitigation from cohort 1 (BAS installed in 1995); (c) Zoomed annual mitigation from Cohort 6 (BAS installed in 2000); (d) Electricity carbon-intensity trend for USA over 1995–2025.

#### 4.4. Implications for future automation and decarbonization strategies

The results underscore the critical and complementary role of BACnet-based BAS in global decarbonization. BAS offer large, immediate mitigation opportunities, particularly in markets with carbon-intensive electricity grids or rapid expansion of commercial building stock. However, their long-term mitigation value depends on how they are deployed and maintained within evolving energy systems. As electricity grids decarbonize, the carbon value of electricity savings decreases, making persistence of BAS performance increasingly important. Policies that support regular recommissioning, advanced controls, and continuous monitoring can preserve savings and slow performance decay across cohorts.

In colder and gas-intensive regions, BAS will continue to deliver strong carbon benefits by reducing natural gas use, particularly in space-heating applications. Prioritizing BAS upgrades, heating optimization, and integration with heat electrification strategies can amplify these benefits. As electricity grids become cleaner, each kilowatt-hour saved leads to less carbon mitigation than before. However, BAS can still provide substantial climate value by helping buildings shift their electricity use to times when renewable energy supply is high or grid emissions are low.

## 5 CONCLUSIONS

This study provides a multi-region, cohort-based assessment of long-term carbon mitigation from commercial building automation systems. By integrating BACnet-based BAS adoption dynamics with regional energy use patterns and carbon-intensity trajectories, the analysis quantifies both historical and near-future mitigation impacts at a global scale. Several key conclusions emerge:

1. BAS with BACnet protocol adoption generate substantial cumulative carbon mitigation. Globally, BACnet-based BAS mitigated an estimated 1,401 million tonnes of CO<sub>2e</sub> between 1995 and 2025. With continued adoption through 2030, global cumulative mitigation is projected to reach 2,065 million tonnes, highlighting the long-term climate value of automated building control. BACnet's role as an open, non-proprietary communication protocol in commercial buildings has been central to enabling this global scale of automation.
2. Regional mitigation patterns reflect differences in climate, building energy use, and fuel mix. In the United States, mitigation is dominated by electricity savings because of high cooling, lighting, and plug loads combined with historically carbon-intensive grids. In contrast, Europe and Canada exhibit comparable or greater mitigation from natural gas, driven by colder climates, long heating seasons, and extensive use of gas-based HVAC systems.
3. Annual mitigation increases as BACnet-based BAS cohorts accumulate, but the pace of growth slows after the mid-2010s because electricity grids decarbonize, reducing the CO<sub>2e</sub> avoided per kilowatt-hour saved. In contrast, mitigation from natural-gas savings remains strong since the carbon intensity for natural gas remains largely unchanged over time.
4. Cohort-level dynamics reveal both performance decay and lower post-replacement peaks. BACnet-based BAS savings consistently decline over time due to sensor drift, overrides, and operational changes, and although system replacement restores energy efficiency, continuing grid decarbonization leads to reduced carbon benefits in later years. These dynamics highlight the importance of BAS maintenance in sustaining long-term carbon mitigation. As BAS become more interconnected through BACnet, opportunities increase for centralized monitoring, advanced analytics, and automated fault detection—tools that can help maintain savings and slow performance decay over time.

## 6 ACKNOWLEDGMENT

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**APPENDIX 1. Total floor area of commercial buildings (Billion ft<sup>2</sup>) in the United States, Europe, and Canada from 1995 to 2025**

Table 4 Total floor area of commercial buildings (Billion ft<sup>2</sup>) in each region

Year	USA (B ft <sup>2</sup> )	Europe (B ft <sup>2</sup> )	Canada (B ft <sup>2</sup> )
1995	58.6	55.6	6.0
1996	60.2	57.2	6.2
1997	61.9	58.8	6.3
1998	63.5	60.3	6.4
1999	65.2	61.9	6.5
2000	66.8	63.5	6.6
2001	68.5	65.1	6.7
2002	70.2	66.6	6.8
2003	71.7	68.1	6.9
2004	73.5	69.8	7.0
2005	75.1	71.4	7.1
2006	76.8	72.9	7.2
2007	78.4	74.5	7.3
2008	80.1	76.1	7.4
2009	81.7	77.6	7.5
2010	83.4	79.2	7.6
2011	85.1	80.8	7.7
2012	87.1	82.7	7.8
2013	88.4	83.9	7.9
2014	90.0	85.5	8.0
2015	91.7	87.1	8.1
2016	93.3	88.7	8.1
2017	95.0	90.2	8.2
2018	96.4	91.6	8.3
2019	98.3	93.4	8.4
2020	100.0	94.9	8.5
2021	101.6	96.5	8.5
2022	103.3	98.1	8.6
2023	104.9	99.7	8.7
2024	106.6	101.2	8.8
2025	108.2	102.8	8.8

**APPENDIX 2. Data of electricity carbon intensity (kg CO<sub>2</sub>e/kWh) for the United States, Europe, and Canada from 1995 to 2025**

Table 5 Electricity carbon intensity trends (kg CO<sub>2</sub>e/kWh) in each region

Year	USA (kg/kWh)	Europe (kg/kWh)	Canada (kg/kWh)
1995	0.63	0.45	0.22
1996	0.63	0.43	0.22
1997	0.65	0.42	0.22
1998	0.65	0.42	0.22
1999	0.64	0.41	0.22
2000	0.65	0.39	0.22
2001	0.65	0.39	0.22
2002	0.63	0.39	0.22
2003	0.63	0.39	0.22

2004	0.63	0.38	0.22
2005	0.63	0.38	0.22
2006	0.61	0.38	0.18
2007	0.61	0.39	0.18
2008	0.60	0.36	0.17
2009	0.57	0.35	0.17
2010	0.58	0.34	0.16
2011	0.56	0.34	0.16
2012	0.53	0.34	0.16
2013	0.53	0.32	0.15
2014	0.53	0.31	0.15
2015	0.50	0.31	0.14
2016	0.47	0.30	0.14
2017	0.46	0.30	0.14
2018	0.45	0.29	0.13
2019	0.42	0.25	0.13
2020	0.39	0.23	0.11
2021	0.40	0.24	0.11
2022	0.39	0.26	0.11
2023	0.39	0.26	0.11
2024	0.38	0.25	0.11
2025	0.37	0.24	0.11

**APPENDIX 3. Data of natural gas carbon intensity (kg CO<sub>2</sub>e/ft<sup>3</sup>) for the United States, Europe, and Canada (assumed to be constant in the study period)**

Table 6 Natural gas carbon intensity trends (kg CO<sub>2</sub>e/ft<sup>3</sup>) in each region

Year	USA (kg/ ft <sup>3</sup> )	Europe (kg/ ft <sup>3</sup> )	Canada (kg/ ft <sup>3</sup> )
1995	0.0549	0.06	0.0544

**APPENDIX 4. Data of overall electricity consumption rate (kWh/ft<sup>2</sup>) for commercial buildings in the United States, Europe, and Canada from 1995 to 2025**

Table 7 Overall electricity consumption rate (kWh/ft<sup>2</sup>) for commercial buildings in each region

Year	USA (kWh/ft <sup>2</sup> )	Europe (kWh/ft <sup>2</sup> )	Canada (kWh/ft <sup>2</sup> )
1995	15.3	10.0	13.6
1996	14.7	10.1	13.6
1997	14.7	10.1	13.6
1998	14.7	10.2	13.7
1999	14.6	10.2	13.7
2000	14.6	10.2	13.7
2001	14.6	10.3	13.8
2002	14.6	10.3	13.8
2003	14.6	10.4	13.9
2004	14.5	10.4	13.9
2005	14.5	10.4	13.9
2006	14.5	10.4	14.0
2007	14.4	10.5	14.0
2008	14.4	10.5	14.1
2009	14.4	10.5	14.1
2010	14.4	10.6	14.2
2011	14.4	10.2	14.3
2012	14.3	9.8	14.3
2013	14.3	9.6	14.4
2014	14.3	9.3	14.4
2015	14.3	9.0	14.5
2016	13.1	8.7	14.6
2017	12.8	8.4	14.6
2018	12.4	8.2	14.7
2019	12.0	7.9	14.8
2020	11.7	7.6	14.8
2021	11.3	7.4	14.9
2022	11.0	7.2	15.0
2023	10.7	7.0	15.0
2024	10.4	6.7	15.1
2025	10.2	6.5	15.2

**APPENDIX 5. Data of overall gas consumption rate (ft<sup>3</sup>/ft<sup>2</sup>) for commercial buildings in the United States, Europe, and Canada from 1995 to 2025**

Table 8 Overall gas consumption rate (ft<sup>3</sup>/ft<sup>2</sup>) for commercial buildings in each region

Year	USA (ft <sup>3</sup> /ft <sup>2</sup> )	Europe (ft <sup>3</sup> /ft <sup>2</sup> )	Canada (ft <sup>3</sup> /ft <sup>2</sup> )
1995	48.0	30.0	66.3
1996	47.3	30.0	65.9
1997	46.7	30.0	65.5
1998	46.1	30.0	65.1
1999	45.4	30.0	64.7
2000	44.8	30.0	64.3
2001	44.2	30.0	63.8
2002	43.6	30.0	63.4
2003	42.9	30.0	63.0
2004	42.3	30.0	62.6

Year	USA (ft <sup>3</sup> /ft <sup>2</sup> )	Europe (ft <sup>3</sup> /ft <sup>2</sup> )	Canada (ft <sup>3</sup> /ft <sup>2</sup> )
2005	41.7	30.0	62.2
2006	41.1	30.0	61.8
2007	40.5	30.0	61.3
2008	39.9	30.0	60.9
2009	39.3	30.0	60.5
2010	38.7	30.0	60.1
2011	38.1	30.0	59.7
2012	37.5	30.0	59.3
2013	36.9	30.0	58.9
2014	36.3	30.0	58.4
2015	35.8	30.0	58.0
2016	35.2	30.0	57.6
2017	34.6	30.0	57.2
2018	34.0	30.0	56.8
2019	33.5	30.0	56.4
2020	32.9	30.0	55.9
2021	32.3	30.0	55.5
2022	31.8	30.0	55.1
2023	31.2	30.0	54.7
2024	30.7	30.0	54.3
2025	30.1	30.0	53.9

## APPENDIX 6. BACnet and BAS Adoption Rate Estimates

Table 9 Estimated Adoption rates for BACnet and BAS 1995-2025

Year	BACnet Adoption Rate		BAS Adoption Rate
	North America	Europe	
1995	1.0%	1.0%	5.0%
1996	2.0%	1.3%	5.6%
1997	3.6%	1.8%	6.3%
1998	5.9%	2.4%	7.1%
1999	9.0%	3.1%	8.0%
2000	12.9%	4.1%	8.9%
2001	17.5%	5.4%	10.0%
2002	22.7%	7.0%	11.2%
2003	28.3%	9.0%	12.4%
2004	34.1%	11.5%	13.8%
2005	40.0%	14.6%	15.3%
2006	45.8%	18.2%	17.0%
2007	51.3%	22.2%	18.7%
2008	56.6%	26.7%	20.6%
2009	61.5%	31.4%	22.6%
2010	66.0%	36.2%	24.7%
2011	70.1%	40.8%	26.9%
2012	73.7%	45.1%	29.3%
2013	77.0%	49.0%	31.6%
2014	79.9%	52.4%	34.1%
2015	82.4%	55.2%	36.6%
2016	84.6%	57.5%	39.1%
2017	86.6%	59.4%	41.7%
2018	88.3%	60.9%	44.2%
2019	89.7%	62.0%	46.7%

Year	BACnet Adoption Rate		BAS Adoption Rate
	North America	Europe	
2020	91.0%	62.9%	49.1%
2021	92.0%	63.6%	51.5%
2022	93.0%	64.1%	53.8%
2023	93.7%	64.5%	56.0%
2024	94.4%	64.8%	58.0%
2025	95.0%	65.0%	60.0%

*Estimated BACnet adoption rates based on BSRIA market research studies and ancillary information fitted to a typical sigmoid technology adoption curve. Estimated BAS adoption rates based on contemporary trade publication market data and ancillary information.*

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