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VOLTTRON™: Tech-to-Market Best-Practices Guide for Small- and Medium-Sized Commercial Buildings

July 2016

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U.S. DEPARTMENT OF ENERGY

Prepared for the U.S. Department of Energy
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Pacific Northwest National Laboratory
Richland, Washington 99352

Executive Summary

VOLTTRON™ is an open-source distributed control and sensing platform developed by Pacific Northwest National Laboratory for the U.S. Department of Energy. It was developed to be used by the Office of Energy Efficiency and Renewable Energy to support transactive controls research and deployment activities. VOLTTRON is designed to be an overarching integration platform that could be used to bring together vendors, users, and developers and enable rapid application development and testing. The platform is designed to support modern control strategies, including the use of agent- and transaction-based controls. It also is designed to support the management of a wide range of applications, including heating, ventilation, and air-conditioning systems; electric vehicles; and distributed-energy and whole-building loads.

This report was completed as part of the Building Technologies Office's Technology-to-Market Initiative for VOLTTRON's Market Validation and Business Case Development efforts. The report provides technology-to-market guidance and best practices related to VOLTTRON platform deployments and commercialization activities for use by entities serving small- and medium-sized commercial buildings. The report characterizes the platform ecosystem within the small- and medium-sized commercial building market and articulates the value proposition of VOLTTRON for three core participants in this ecosystem: 1) platform owners/adopters, 2) app developers, and 3) end-users. The report also identifies key market drivers and opportunities for open platform deployments in the small- and medium-sized commercial building market. Possible pathways to the market are described—laboratory testing to market adoption to commercialization. We also identify and address various technical and market barriers that could hinder deployment of VOLTTRON. Finally, we provide "best practice" tech-to-market guidance for building energy-related deployment efforts serving small- and medium-sized commercial buildings.

Acknowledgments

The authors would like to thank Jim Young and Casey Talon of Navigant Consulting, for sharing their insights on the market landscape for transactive controls and intelligent building systems. In addition, we would like to thank Justin Sipe of Transformative Wave for sharing information on building energy service business models as they pertain to small- and medium- sized commercial buildings supported by packaged rooftop heating, ventilation, and air-conditioning systems. We would also like to thank Linda Rankin, of V-SQUARED, for taking the time to share her experiences developing an app on the VOLTTRON™ platform and also sharing her thoughts on the competitive landscape for open multiple-sided platforms serving small- and medium-sized commercial buildings. We would also like to thank Saifur Rahman and Manisa Pipattanasomporn of Virginia Tech's BEMOSS (Building Energy Management Open Source Software) team and Teja Kuruganti of Oak Ridge National Laboratory for their reviews and input on this report. We would also like to acknowledge and thank Adam Regnier and Jin Wen of Drexel University for sharing and summarizing their experiences deploying VOLTTRON as part of their demonstration of a VOLTTRON-compatible diagnostic tool for air handling unit variable-air-volume systems.

The authors would like to thank Jon Thompson of Avista Corp and Larry Lackey of Coergon, for taking the time to review the report and for providing insights from the utility and software industry perspectives, respectively. Finally, we would like to thank Nora Wang and Sriram Somasundaram, both of Pacific Northwest National Laboratory (PNNL), for providing a final review of the report and feedback related to guidance for potential VOLTTRON users.

Acronyms and Abbreviations

AFDD	automated fault detection and diagnostics
ARC	advanced rooftop control
BAS	building automation system
BEMOSS	Building Energy Management Open-Source Software
DOE	U.S. Department of Energy
FDD	fault detection and diagnostics
HVAC	heating, ventilation, and air conditioning
IoT	Internet of Things
IT	information technology
M&V	measurement and verification (building services)
ORNL	Oak Ridge National Laboratory
PNNL	Pacific Northwest National Laboratory
R&D	research and development
RTU	rooftop air handling unit
SMCB	small- and medium-sized commercial buildings

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1.0 Introduction

Homes and commercial buildings account for approximately 40% of total primary energy consumption in the United States (EIA 2015). Much has been said about the significant potential resource and energy savings that could be realized from making buildings more "intelligent," interactive, and responsive to the electric grid. However, although today's buildings contain more technology than ever before, a widely accepted transactive approach and platform to coordinate energy systems in a manner that allows building owners and grid service providers to participate in a shared energy economy is still lacking, but necessary, to efficiently use and conserve resources and balance current and future energy supply and demand, as well as deliver energy-efficiency services.

Although some manufacturers of building equipment and appliances have provided proprietary platforms that provide limited forms of transactive communication and interfaces, these platforms are narrowly applied in most cases and are not compatible with equipment and appliances from other manufacturers. For these reasons, the U.S. Department of Energy (DOE) has invested in the development of VOLTTRON™, which is an open platform designed for use in the building and grid environment. The VOLTTRON platform is a distributed control and sensing software platform designed to manage a wide range of applications, including heating, ventilation, and air-conditioning (HVAC) systems, electric vehicles, and distributed-energy or whole building loads. With VOLTTRON, software agents allow communication between the power grid and physical devices or systems in a building to coordinate energy use and shift energy load to off-peak times; VOLTTRON also enables communication between devices within a building and between buildings in a campus setting, and facilitates the delivery of energy-efficiency services to buildings.

VOLTTRON has moved from the laboratory conceptual stage of development and is currently being field tested and applied in a number of building and grid applications. This report examines some of the initial deployment activities and provides a best practice technology adoption guide for use by entities serving the small- and medium-sized commercial buildings (SMCB) market. In this report, the value proposition of VOLTTRON for SMCBs is described, identifying possible pathways to commercialization as well as barriers and challenges to market adoption and acceptance. Finally, we provide recommendations on how to overcome these challenges.

2.0 Background

First developed by Pacific Northwest National Laboratory (PNNL) as part of its Future Power Grid Initiative, VOLTTRON is an open-source distributed control and sensing platform designed to support modern control strategies, including the use of agent- and transaction-based controls. It enables mobile and stationary software agents to perform information gathering, processing, and control actions. VOLTTRON is designed to be an overarching integration platform to foster collaboration among vendors, users, and developers and enable rapid application development and testing.

PNNL developed and transferred VOLTTRON to energy-efficiency providers to provide an extensively tested resource for building applications that improve energy efficiency as well as grid reliability and security in buildings and associated electric and energy-consuming devices powered by VOLTTRON. To develop, test, and transition it to the commercial market, DOE and PNNL have made VOLTTRON available as an open-source, no-cost[1] code to allow for broad, flexible use. Mechanisms for transfer of the platform to users are listed below:

1. Active partnership and funding through DOE's Office of Energy Efficiency and Renewable Energy with research and development (R&D) at both academic institutions and commercial entities providing building energy and grid services.
2. Bi-weekly "Office Hours" during which users call in for assistance and information, allowing users to resolve questions quickly and simplifying the technical transfer process for new users so they can begin using the platform immediately.
3. Outreach, including demonstrations, at energy- and technology-related meetings, such as those hosted in 2014 at Case Western Reserve University[2] and in 2015 by Virginia Tech.[3]

These efforts yield information and lessons-learned that are examined and synthesized as part of this report to inform the technology-to-market best practices for VOLTTRON.

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[1] VOLTTRON is being distributed under a Berkeley Software Distribution-style, open-source license, where users are permitted to use VOLTTRON in whatever manner they see fit, providing that proper attribution is given to Battelle, as described in the license language. This could include the development of proprietary derivative products. Additional code and security features for VOLTTRON are available through a separate license agreement.

[2] Meeting material available online at: http://energy.gov/eere/buildings/downloads/technical-meeting-software-framework-transactive-energy.

[3] Meeting material available online at: http://energy.gov/eere/buildings/downloads/technical-meeting-software-framework-transactive-energy-volttron-2015.

3.0 Scope

This report focuses on the market application and commercial opportunities of VOLTTRON in the SMCB market, where the buildings are defined as those that are 50,000 square feet (ft^2) in floor area or less. This segment of the commercial buildings sector represents nearly 95% of all buildings (EIA/CBECS 2012). For SMCBs, a low-cost open platform that facilitates transactive communication and integration of building energy systems can be particularly beneficial and instrumental in enabling efficient and integrative use of resources. The reason for this is small commercial buildings are typically less sophisticated and less automated[4] than their larger building counterparts, and the resources they have available to devote to energy management are constrained. Nevertheless, SMCBs consume approximately 60% of the energy used by all commercial buildings, and the potential for energy savings, in terms of efficiency and operational improvements are significant and well documented (e.g., Katipamula et al. 2012, NIBS 2014, Wang et al. 2013).

One of the key benefits of a transactive control platform, such as VOLTTRON, is that it can bring multiple sides of the market together, including the electric grid and building systems and services. This opens the door to integration and communications between internal building functions with centralized grid services, distributed renewable energy sources, energy storage, and electric vehicle charging mechanisms. For this report, however, we focus on assessing the capabilities and potential of VOLTTRON as a platform within the SMCB domain in terms of improving energy efficiency and end-use load management of building energy systems.

Figure 3.1 provides a summary list of the key stakeholders, customers, and sources of R&D for energy services in the SMCB market, described in terms of a platform environment or ecosystem.

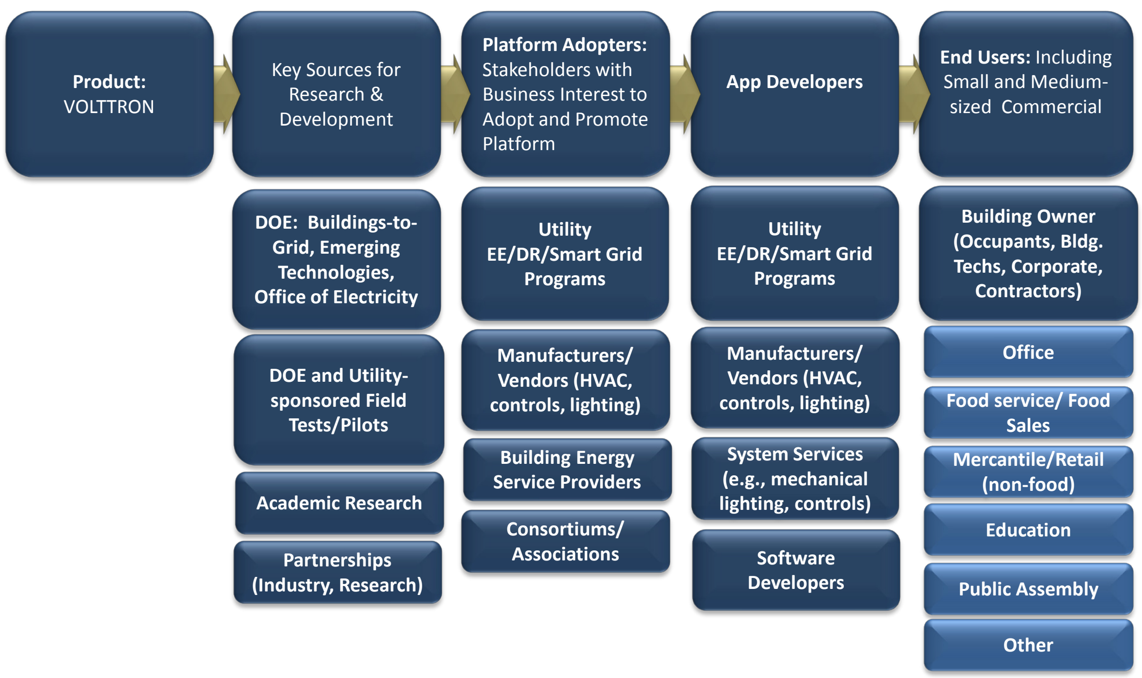

Figure 3.1. Platform Ecosystem and Market Landscape for VOLTTRON (as related to SMCB)

[4] Most buildings in the small building category do not have building automation systems (EIA/CBECS 2012).

Market research suggests that the most successful multi-sided platforms in the market today started out as successful standalone products or one-sided platforms; therefore, this study examines the capabilities and potential of VOLTTRON in the SMCB end-user services market. Because the fate of the platform and the applications (apps) built on the platform are intertwined, this report examines how these participant exchanges and relationships (e.g., among the platform, its apps, and end-users) have played out in the field for the SMCB market (Rysman 2009).

3.1 The Platform Ecosystem

Because VOLTTRON is a platform, it must serve the participants of the "platform ecosystem"[5] to be valuable and sustainable. As an enabling technology, the VOLTTORN platform does not yield benefits in and of itself; rather, the value proposition of this technology depends on how effective it is at facilitating valued interactions between multiple market participants. When discussing the "market" for VOLTTRON, it is important to recognize the distinctive value propositions it offers these participants, as described below:

1. *Platform owners/adopters*: These are the entities that adopt VOLTTRON as a platform for enabling grid- and/or building-related services and applications that can leverage the platform for their own uses. As shown in Figure 3.1, platform adopters within the SMCB market would include electric utilities and building energy service providers. Adopters could also include manufacturers and vendors of building equipment and appliances that may have their own proprietary software on which they build services, but it could realize benefits from adopting an open platform, such as VOLTTRON. Eventually there could be associations or consortiums related to grid and building services that may realize that it would be beneficial for their constituents to promote an open platform on which to develop business models and rules of governance. Active platform participants in the ecosystem that would likely influence adoption and could also eventually participate as platform adopters could include building owners, lessors and lessees, aggregators, and building occupants.
2. *App Developers*: The "app" in this case would be an add-on software subsystem or grid/building service that is hosted on to the VOLTTRON platform to add functionality to it. As shown in Figure 3.1, App developers could include all kinds of software developers; however, in the current building environment, these software developers would typically be associated with businesses that provide building energy or other building services. It could also include manufacturers or building equipment service providers who could build applications specific to the services they provide on the open platform. Utilities or entities providing services to utilities also could develop applications specific to their services and regional needs.
3. *End-Users*: The end-user in this case would be the commercial building owner, operator, occupants, corporate decision-makers, and/or contractors with building management and maintenance responsibilities.

Each of these participants has different needs and motivations for participating in an open platform ecosystem.

[5] Terminology borrowed from Amrit Tiwana's 2014 book on the topic, *Platform Ecosystems: Aligning Architecture, Governance, and Strategy*. Morgan Kaufmann, first edition (December 16, 2013).

3.1.1 Small- and Medium-Sized Commercial Buildings (end-users)

To understand the needs and motivations of end-users, it is important to understand SMCBs; for example, the types of businesses and occupants they house, how they consume energy, the types of HVAC systems they use, etc. Based on DOE's most recent Commercial Buildings Energy Consumption Survey (EIA/CBECS 2012), SMCBs include many types of buildings, but based on floor space, mercantile/service (21%), office buildings (18%), public assembly/religious worship space (16%), education buildings (8%), and food-service/food sales (7%) are the most predominant building types.

Approximately 85% of SMCB commercial floor space is privately owned while 15% is government owned (mostly by local governments of which a large percentage is for schools). Of the privately owned floor space, about 50% is owner-occupied, 40% is leased, and just over 10% is both owner-occupied and leased space. In most buildings (85%), the building owner is responsible for all energy equipment investments and maintenance (EIA/CBECS 2012).

Only about 11% of these SMCBs have building automation systems (BAS) (EIA/CBECS 2012), and over half of the energy consumed in these buildings is from HVAC and refrigeration equipment (EIA/CBECS 2012). Just over 60% of the energy consumed in grocery stores and restaurants (i.e., supermarkets, food sales, etc.) is from refrigeration and cooking equipment. Because of these usage characteristics in smaller commercial buildings, this report primarily focuses on the applications of the VOLTTRON platform with respect to HVAC and refrigeration (see Figure 3.2 and Section 3.1.2).

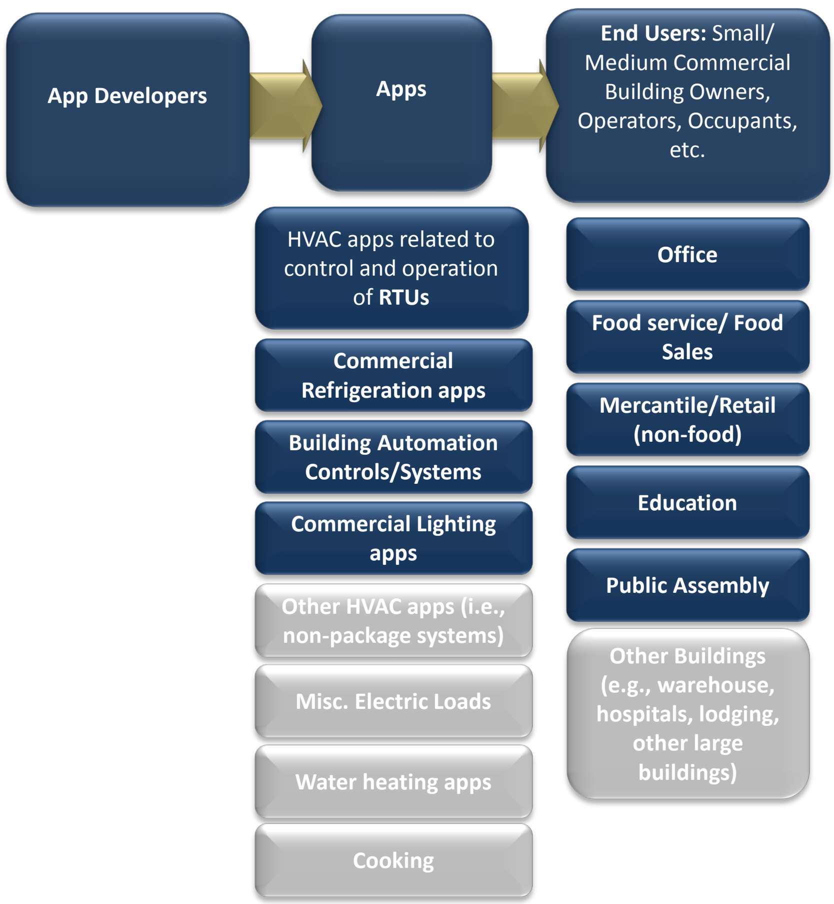

Figure 3.2. Predominant Applications in Small- and Medium-Sized Commercial Buildings

3.1.2 System Applications (app developers)

Direct expansion packaged HVAC systems (commonly referred to as rooftop units [RTU]) are the most common HVAC systems employed to meet the heating and cooling needs of SMCBs. In general, any app that is designed to improve the performance of RTUs could have significant energy efficiency and comfort impacts for SMCB end-users. Five well known manufacturers of commercial HVAC equipment dominate the HVAC market: Carrier, Lennox, McQuay, Trane, and York (Brambley et al. 2011).

Approximately 37,000 supermarkets in the United States consume over a 1000 MWh of electricity for commercial refrigeration each year (Wallace 2015). Typical commercial refrigeration installations include compressor racks, display cases, condensers, walk-in coolers and freezers, and ice machines. For supermarket chains, which typically operate their stores on very narrow profit margins, energy is a substantial portion of operating costs. In addition, the average supermarket spends roughly $100,000 annually on maintenance and repairs for HVAC, refrigeration, and lighting (Navigant 2009).

As previously mentioned, BASs are relatively rare in SMCBs. Rather, a large portion of the current controls in SMCBs are relatively simple set-point-based controls. Typically, there is a programmable controller with a predefined control scheme that is executed based on sensor data (e.g., temperature). In the past 5 years, an increasing number of communicating-and-learning thermostats have become commercially available that are compatible with most packaged HVAC systems and use standard connections to facilitate control (Katipamula et al. 2012). As part of this report, we examined the compatibility and application of an assortment of typical SMCB controllers and control strategies implemented on the VOLTTRON platform as part of the case studies.

For a platform to offer value in SMCBs, it must be compatible with the needs of app developers working with packaged systems, automated controls typical of smaller buildings, and refrigeration systems (for food sales and food service); therefore, most of the case studies implemented and examined as part of this study focus on these specific technologies and applications.

3.1.3 Platform Adopters (grid and building energy service providers)

Within the SMCB market, the platform adopter often is the app developer also. For example, Transformative Wave, which provides energy-efficiency solutions for RTUs and other building systems, has adopted the VOLTTRON platform for its CATALYST retrofit application for RTUs. It uses the platform and builds applications on the platform to address the needs of its consumers, which primarily are SMCB owners whose buildings are equipped with RTU systems. Within the platform ecosystem, the decisions and role of the app adopters are distinct from the app developer in that they have business interest to adopt and promote the VOLTTRON platform.

4.0 Benefits of VOLTTRON

To be successful and sustainable as an open platform that brings multiple parties together, the platform must meet the distinctive needs of multiple participants in the platform ecosystem, *and* it must do so in a more compelling manner than a standalone product or service business model. As previously discussed, because the VOLTTRON platform is an enabling technology and therefore does not yield benefits by itself, the value proposition of this technology depends on how effective it is at facilitating valued interactions between multiple market participants. To provide value within this ecosystem, a platform must be able to easily integrate multiple systems and create better solutions.

The move to an open platform should yield benefits in terms of adding features and functionality to software and enabling integration of various systems to provide more robust and more easily accessible information. It also should provide better solutions in that an open platform gives access to more people who can add, improve, and expand on the platform in a manner that could facilitate the broad adoption of the platform. Ideally, as the community of developers begins to collaborate, exchange ideas, and build specific solutions, the better the solutions become. An open platform should reduce the operation, installation, programming, and the overall integration costs. It should improve the overall cost-effectiveness of the end product for the end-user, and custom applications should be available without having to employ multiple vendors for multiple systems, which allows the end-user to avoid paying a premium for customization.

4.1 Value Proposition within Platform Ecosystem

Considering these overall benefits and advantages of an open platform, we turn our focus to whether VOLTTRON can deliver such benefits in the SMCB market. VOLTTRON is designed to be a secure, extensible, and modular technology that supports a wide range of applications. It is equipped to communicate with building systems (e.g., Modbus or BACnet devices) and external services, and has a built-in data historian and weather service. It supports open utility communication protocols (e.g., OpenADR 1.2), and has a flexible messaging system (publish/subscribe) as well as utility and supporting classes to simplify application development and a logging service for saving application results and logging information. It is an interoperable reference platform for transactive energy applications, and it has great potential capabilities in enabling the integration of buildings and the grid, as well as delivery of energy-efficiency services. To assess if and how these features translate to benefits for the SMCB market, we evaluated the value proposition for all the platform participants in the SMCB market and assessed whether the attributes of the VOLTTRON platform can be realized as benefits for these participants.

Table 4.1 summarizes the value proposition for each of the platform participants and maps them to specific VOLTTRON attributes that enable benefits for each participant.

Elements of the value proposition for platform adopters are described below:

- *Reduces costs and distributes risks*: For VOLTTRON to achieve these benefits, adoption costs must be kept low. Even though it is an open platform available to users at no cost, it is essential that the costs of implementation (i.e., startup and learning) and maintenance (e.g., storage and memory requirements, updates, etc.) also are kept low so those adopting the platform will realize cost reductions. The multi-sided open platform also distributes risk between app developers and platform adopters, reducing the overall risk burden to each platform participant.

- *Greater functionality and promotion of innovation:* It also must offer a communication platform that adds value and facilitates clear communication and compatibility with other systems. To facilitate innovation, the security features of the platform must be robust and stable. In addition, a modular system promotes innovation on a broad scale without the fear of one application interfering with another. Over the long term, a platform that is designed to be extensible allows the platform to evolve with changing market conditions, thus making it more sustainable over the long term.

Elements of the value proposition for app developers are discussed below:

- *Reduces costs and sharpens focus on app development*: Platforms enable app developers to use the core capabilities of the platform as the foundation for their own work instead of replicating the functionality that their apps share with other apps. Their upfront investment is therefore limited to functionality that their apps do not share with others. It gives them the advantages of scale without the cost of ownership by piggybacking on the platform.
- *Market networks and access*: If an open platform has the potential to be broadly accepted and adopted, an open platform can provide access to a pool of customers, who can more easily find the app developer's work and more efficiently transact with them. An accepted open platform can reduce search costs and transaction costs between app developers and their prospective customers.

From the app-developer perspective, if VOLTTRON becomes an accepted platform in the buildings market, it can provide the potential of a continuous revenue stream as well as reduce development costs if "easy," low-cost app development is supported. A platform that is flexible, language-agnostic, and interoperable across multiple vendors and applications can help keep costs low to the app developer and improve their market networks and potential scale of the application. In terms of the SMCB market, the platform should facilitate, or at least not prohibit, potentially high-value applications, such as demand-response and other utility linkages and services.

The three elements of the value proposition for end-users are described below.

- *Better customization*: The primary value proposition of the open platform for end-users is that it can more uniquely be customized to their idiosyncratic needs by mixing and matching apps from a diverse pool.
- *Faster innovation and better networks*: End-users also benefit from the accelerated pace of innovation around their investment in the platform, with the added prospect of increasing value over time.
- *Lower search costs and transaction costs*: If a platform becomes widely accepted, it can reduce search and transaction costs associated with finding and acquiring apps relative to doing the same without a platform in the middle.

In the end, for the platform to be sustainable, all of these features and benefits to platform participants must translate into benefits to the commercial building end-user. These benefits should include lower energy costs, both through improved system efficiency and through lower peak demand charges, improved comfort for occupants, improved performance of energy systems over time, improvements or maintenance of building security, and increased productivity. If the open platform facilitates better customization to these end-users' needs, then accelerated innovation, and potentially lower search costs (if the platform becomes trusted and reliable), can be benefits realized by end-users; however, these may not be immediate outcomes as they rely on the platform adopter and app development process to be in place and well established.

Table 4.1. Value Proposition for Platform Participants

Platform Participant	Value Proposition	Attributes Creating Value in an Open Source Community
Platform Adopter	• Reduces Costs • Risk Distribution • Greater Functionality • Promotes Innovation	• Low-cost implementation • **Low-cost maintenance** (e.g., central processing unit storage and memory requirements, updates) • Communication platform • Robust **Security** features • **Compatibility** with current and legacy systems • Modular • Extensible
App Developer	• Reduces Costs of app development and scale up • Improves Market Networks and Access	• Low-cost app development • **Flexible** (e.g., language-agnostic and functional in cloud) • **Interoperable** across vendors and applications • Can support **Demand Response** (utility linkage)
End-User (Small Commercial Building Owners/Users)	• Better Customization to Needs • Faster Innovation • Improved Networks • Lower Search and Transaction Costs	• Better customization and improvements to end-user needs, including: – Building occupant **comfort** – Building productivity – Building **energy** systems – Building **security** – Lower operational costs (e.g., avoiding peak charges, efficiency, etc.)

4.2 Case Studies Demonstrating VOLTTRON Benefits in the Small- and Medium-Sized Commercial Buildings Market

To facilitate the commercialization of VOLTTRON, DOE and PNNL developed and transferred the VOLTTRON source code to commercial and academic energy-efficiency providers. This transfer was done at no cost on a non-exclusive basis to provide a tested resource to build applications for improving energy efficiency, grid reliability, and security in buildings and associated electric and energy-consuming devices. The first major academic and commercial users of the VOLTTRON software platform included Transformative Wave Technologies, Virginia Tech, Drexel University, Emerson Climate Technologies, and Quality Logic. The summary conclusions and insights described throughout this section are based on stakeholder workshop presentations and discussions with these users.[6]

The case studies carried out by known platform adopters and app developers are summarized in Appendixes A and B. Table 4.2 is a preliminary and non-exhaustive effort to summarize, *as of the date of this report,* the outcomes for some of the case studies in terms of how the VOLTTRON platform performed and generated value with respect to the identified attributes. To develop this evaluation, we

[6] See summary of workshop and downloadable presentations at the Energy.gov website at: http://energy.gov/eere/buildings/downloads/technical-meeting-software-framework-transactive-energy-volttron-2015.

reviewed known case study documentation and reports related to SMCB applications, presentations of outcomes held during two stakeholder technical meetings, and solicited feedback from researchers. Many of the case studies were narrowly applied; therefore, specific attributes may not have been observed in enough depth to provide an evaluation. When insufficient information was available to observe the performance of VOLTTRON for a specific attribute, the relevant cells in Table 4.2 are left blank.

In a number of cases, the key contributing attributes were observed and study participants confirmed that VOLTTRON added value by reducing costs, improving functionality, and providing a stable foundation on which to innovate and build low-cost applications.

4.2.1 Reduces Costs

Several case study participants confirmed that VOLTTRON both lowered the cost of implementation and integration of a particular application as well as provided a very good platform for low-cost app development.

Implementation and App Development

> "VOLTTRON provided a great platform for fast, low-cost app development."
>
> Linda Rankin, Quality Logic Consultant

VOLTTRON was designed for small computing devices (e.g., Raspberry Pi, BeagleBone Black, etc.), and the platform itself was designed to use minimal resources. This allows VOLTTRON to run on inexpensive commodity boards, which greatly reduces hardware costs for its deployment and makes it more cost effective for SMCB use cases. One of the primary goals of Virginia Tech's Building Energy Management Open-Source Software (BEMOSS) pilot program was to demonstrate the capabilities and effectiveness of VOLTTRON with regard to developing an operating system for building systems that serve SMCBs. A key goal of this program was to maximize energy savings subject to very rigid cost constraints, as would be typical in an SMCB application. Thus far, BEMOSS has demonstrated multiple "plug-and-play" applications where it can automatically discover supported load controllers including smart thermostats, variable air volume/RTUs, lighting loads, and plug-load controllers. Based on demonostration results, the BEMOSS research team concluded that VOLTTRON was interoperable between devices made by different manufacturers and cost effective to deploy in SMCBs.[7]

Emerson Climate Technologies' researchers commented that the portability and flexibility of the open Python coding language reduces the implementation costs of adopting the platform. Quality Logic used VOLTTRON to develop an application for electric vehicle charging and coordination between buildings and concluded that the VOLTTRON platform provided an extremely easy, low-cost platform on which to develop applications relative to other platforms in the market.

[7] For a summary of recent findings on BEMOSS project, see "Building Energy Management Open-Source Software (BEMOSS)," presentation, available from DOE's website at http://energy.gov/sites/prod/files/2015/08/f25/08.%20BEMOSS_VOLTTRON_meeting_V3.pdf.

Table 4.2. Preliminary and Non-Exhaustive Evaluation of VOLTTRON Performance Outcomes, as of April 30, 2016. (Based on available case study documentation and reports, presentations at technical meetings, and feedback from researchers,)

		Observations in the Field										
Case Study	Application	*Low-Cost Implementation*	*Low-Cost Maintenance*	*Communication*	*Security*	*Compatibility*	*Modularity*	*Extensible*	*Low-Cost App development*	*Flexibility*	*Interoperability*	*Supports Demand Response*
Transactive Wave CATALYST Retrofit – Multiple Commercial Buildings	RTU CATALYST retrofit	✓+	✓+	✓	✓	✓	✓	✓	✓	✓	✓+	✓
Transactive Wave CATALYST Retrofit – Multiple Commercial Buildings	BAS interaction	✓	✓	✓	✓			✓	✓	✓	✓	✓
BEMOSS (Virginia Tech)	BAS/building energy management (configured for SMCB) for monitoring and control of HVAC, lighting, and plug loads	✓+	✓	✓+	✓	✓+	✓	✓	✓	✓+	✓	✓
Autonomous Control for HVAC (Oak Ridge National Laboratory [ORNL])	RTU thermostat centralized control and coordination	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Supermarkets (Emerson/ORNL)	Refrigeration (defrost control)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Automated Fault Detection and Diagnostics (Drexel University – multiple buildings)	AFDD for air handler unit-variable air volume systems	✓+	✓	✓	✓	✓	✓		✓+	✓	✓	✓
LBNL Transactional Network Applications (LBNL 2014)	Lighting diagnostic agents	✓+	✓	✓					✓	✓+		
LBNL Transactional Network Applications (LBNL 2014)	Demand response (various components)	✓+	✓	✓					✓	✓+		✓
Transactive Control Node (Quality Logic)	Transactive control node app development								✓+	✓+	○	

<u>Keys</u>

Significant Benefit Realized in Field	✓+
Potential Benefits (but further validation needed)	✓
Needs Improvement	○
Not Addressed, Examined, or Observed	Blank

To help keep implementation and app development costs low, the VOLTTRON development team holds regular “Office Hours” during which members of the team are available to discuss new features and plans as well as answer questions from the user community. These questions range from the basics of how to get started with the platform, how to build V-agents,[8] and taking deep dives into the code itself. The VOLTTRON community spans a wide range of experience in the domains of buildings and computer science. For some users, this is their first foray into working in Linux and programming in Python. At the "Office Hours" and follow-up meetings the VOLTTRON team works through problems users may have to ensure they can start working on their innovative research and not just learning to use the platform. VOLTTRON also has a detailed user guide, wiki, and white papers that provide additional resources to those working with the platform. The user guide provides step-by-step instructions for getting started while the wiki contains details of various components of the platform.

Flexibility and Compatibility

A Transformative Wave representative noted that there were cost benefits in moving away from proprietary servers and that they planned to add the VOLTTRON platform to their programming capabilities. This would allow them to move away from proprietary servers and build out their own services on VOLTTRON. VOLTTRON's cloud-based capabilities will enable Transformative Wave to both expand and cut the costs of their services to small building customers.

VOLTTRON has been designed to be open and flexible to allow it to work with a wide variety of devices, protocols, and other platforms. This integration allows each platform to play to its strengths and enrich the solution space by avoiding "either/or" decisions. VOLTTRON isolates the details of communicating with devices from the actors in the platform. This allows application developers to work with data coming from the message bus without having to worry about the details of its origin. Data collected via BACnet, MODBUS, or a custom protocol looks the same to all applications. This design can ease integration of legacy systems by hiding any complexities of interacting with a device. If the device can be made to interact (through existing input/output or via retrofit) it can participate in the platform.

ORNL has implemented VOLTTRON on a modified thermostat with an added compute and communication board to deploy autonomous peak-load reduction control with a simple replacement of thermostats in a SMCB. The VOLTTRON-enabled thermostats can coordinate among themselves to reduce peak demand in a given building while maintaining occupant comfort.

Communication and Security

Transformative Wave is a building energy service provider that has developed a retrofit control kit (CATALYST) that combines energy-saving measures with fan controls for single-zone RTUs. In partnership with DOE and PNNL, Transformative Wave adopted the VOLTTRON platform and tested it in SMCB applications of its CATALYST system. As part of the testing, Transformative Wave concluded that, by leveraging the VOLTTRON communication and security platform, they were able to reduce implementation costs of their CATALYST system (Transformative Wave 2015). In addition, Drexel University researchers found that the VOLTTRON platform provided a way to easily compare and combine solutions from different

> "By leveraging VOLTTRON's communication platform, we are able to devote our core development efforts in other areas."
>
> Justin Sipe, Transformative Wave

[8] The "V-Agent" is a process executing within the VOLTTRON platform, communicating on the message bus. V-Agents are distinguished from traditional definitions of software agents because some V-Agents encapsulate applications that are not true "agents."

organizations by connecting various “agents,” with communication facilitated across VOLTTRON’s message bus.[9]

Two key drivers for developing the VOLTTRON platform are security and resource management. Security is built into the platform and not bolted on as is frequently the case in other platforms, especially in the research realm. Cyber-security specialists on the development team ensure that every feature and facet of the platform keeps security in mind. The security features of VOLTTRON would be expected to reduce platform maintenance costs over time. In addition to reducing costs, other benefits were noted related to VOLTTRON’s communication and security attributes, which are discussed in Section 4.2.4 of this report.

4.2.2 Improves Functionality and Supports Innovation

According to Transformative Wave, their current CATALYST solution is cost effective for large RTUs where the larger the RTU capacity, the shorter the payback period. In this field, a simple payback period of less than 3 years is needed for any retrofit of an RTU. By reducing implementation costs and adding additional application support, Transformative Wave could potentially and cost effectively extend the application of the CATALYST retrofit kit to smaller RTUs serving smaller commercial buildings, such as small office buildings and quick-service restaurants. Transformative Wave representatives concluded that the VOLTTRON platform could be used as a tool kit to expand capabilities and help achieve their long-term goals in the SMCB market (Transformative Wave 2015).

Emerson Climate Technologies is one of the leading providers of HVAC and refrigeration solutions for SMCBs. They tested the VOLTTRON platform for grid and energy-efficiency services applied to refrigeration equipment serving convenience stores and supermarkets, which make up a significant portion of their service portfolio. Because supermarkets only have a 1 to 2% profit margin, it is essential that any retrofit meet very rigid cost-effective criteria. For the Emerson pilot carried out in partnership with ORNL, researchers developed an algorithm to perform defrost-on-demand using a VOLTTRON platform and control app modification to one of Emerson’s E2 controllers. Initial testing showed up to 75% reduction in defrost energy, which equates to approximately 39,650 to 57,900 kWh savings per store per year.[10] As a result of these successful tests, Emerson is considering further testing of the VOLTTRON platform and developing additional energy-related apps for supermarkets on the platform (Wallace 2015).

With the Drexel University pilot program, researchers developed a cost-effective automatic fault detection and diagnostics (AFDD) tool that integrates both statistical process control and machine learning techniques and rule-based methods to achieve a whole building energy system fault diagnosis. The AFDD system is built on the VOLTTRON platform to improve its “plug-and-play” capability. Although research is ongoing for this effort, initial results have demonstrated that VOLTTRON is capable of supporting this AFDD application where faults were detected in 93% of the cases in which deviations were present. Overall, researchers found that the key benefit of using the VOLTTRON platform was that it added functionality and the ability for researchers or companies to spend more time on the value-added portion of their work, and less time dealing with connectivity and data-handling issues that often can be extremely time-consuming (i.e., nonproductive) for researchers.[11]

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[9] Regnier, A and J Wen. 2016. “Summary of VOLTTRON Deployment and Experiences at Drexel University.” Unpublished white paper documenting field observations, Drexel University. Philadelphia, Pennsylvania.
[10] For reference, the overall mean average size of food-sales stores is about 7000 ft^2 (CBECS 2012).
[11] Regnier, A and J Wen. 2016. “Summary of VOLTTRON Deployment and Experiences at Drexel University.” Unpublished white paper documenting field observations, Drexel University. Philadelphia, Pennsylvania.

4.2.3 Expanded Market Networks and Access

Although it is challenging to foresee how the outcomes and results in pilots and case studies might achieve significant scale up in the market over the next decade, there are several features of VOLTTRON that have been field demonstrated and show promise with regard to its ability to support larger-scale deployment and expansion of certain applications. In particular, the BEMOSS experimented with VOLTTRON's capability to flexibly support multiple apps and interoperability with multiple controllers, communication technologies, and protocols. The VOLTTRON platform successfully supported multiple systems, and integrated communication and control for building energy management applications through Virginia Tech's BEMOSS platform that added 1) a number of agents, 2) API (application program interface) interfaces for selected devices, 3) a web-based user interface, and 4) selected applications for intelligent load control, including scheduling, alarm/notification, and demand response.

Tranformative Wave also indicated that VOLTTRON's capability to support demand response and OpenADR (a standard communication protocol for demand response) without any additional hardware changes potentially opens up a whole new market for energy services and app development within SMCBs. Once a company overcomes the software development burden with the new demand-response protocols, it could leverage extra incentive dollars from utilities. Having additional demand-response capabilities would improve market access and networks for app developers and energy service providers; however, the market network potential is dependent on utility acceptance in program development in this area.

Nevertheless, Transformative Wave noted that there could be a significant improvement in paybacks from leveraging the VOLTTRON communication platform for their CATALYST system and using VOLTTRON to support demand-response applications. The ability to operate both energy efficiency and demand response on the same platform is of particular benefit to building energy services that focus on HVAC controls. Transformative Wave noted that even though they did not expect some of the added features to increase business sales immediately, they were hopeful that they could grow their SMCB program significantly over time and make it a major part of their business.

The fact that the VOLTTRON platform can support cloud-based applications also opens the door to expanded networks and cost-effective applications for smaller buildings and buildings that are managed as individual portfolios under one energy management system. By operating in the cloud, building energy service providers are able to leverage existing infrastructure and scale to multiple buildings and systems more easily, making the services more cost effective in the smaller commercial building market. They also can more easily integrate multiple building management systems and provide add-on services for a nominal fee when using a cloud-based approach.

4.2.4 Other Benefits

Although communication and security features of the platform primarily exist to support the overall infrastructure on which to innovate, these features can be perceived as benefits in and of themselves. The threat of cyber-attacks, in general, makes security a prime feature and selling point for a platform. Traditionally, cyber-security has been a big concern for utilities and larger companies with large amounts of customer data; however, as more small businesses and companies grow dependent on cyber-connectivity for everyday applications, the need and interest in cost effectively strengthening cyber-security features of their buildings has increased. As the National Academies states (NAFCC 2015),

> "The nation's buildings are increasingly relying on building control systems with embedded communications technology and many enabled via the Internet. These systems provide critical

> services that allow a building to meet the functional and operational needs of building occupants, but they can also be easy targets for hackers and people with malicious intent. Attackers can exploit these systems to gain unauthorized access to facilities; be used as an entry point to the traditional informational technology (IT) systems and data; cause physical destruction of building equipment; and expose an organization to significant financial obligations to contain and eradicate malware or recover from a cyber-event… These facilities contain building and access control systems such as heating, ventilation, and air conditioning...that are increasingly being automated and connected to other information systems or networks and the Internet. As these systems are becoming more connected, so is their vulnerability to potential cyber-attacks."

As part of the BEMOSS demonstration, researchers found that they could use the built-in security features for SMCB applications in VOLTTRON, including V-Agent authorization and authentication, encrypted multi-layer communication, and V-Agent validation. In addition, some case study participants believed the VOLTTRON communication platform alone generated value to their processes and services devoted to HVAC systems. VOLTTRON has been designed to be open and flexible to allow it to work with a wide variety of devices, protocols, and other platforms. Through the use of translation V-Agents, VOLTTRON can enable communication and integration with other platforms which may work with a different ecosystem of devices and applications.

5.0 Pathways from Lab to Market

The road to market for an open-source platform functioning in the SMCB environment must be navigated recognizing both the platform ecosystem and what drives the end-user's building energy system decisions.

One of the key hurdles that must be overcome for any platform to gain market acceptance is the so-called "Catch 22" effect where a platform cannot attract app developers unless it has a large base of end-users, and a large base of users is unlikely to join unless a platform has a large variety of apps available that end-users perceive as valuable. This is one of the primary reasons why DOE supported the development of VOLTTRON through its Building-Grid Initiative. The presence of DOE's R&D resources provides a stable development environment for the open platform and helps assure potential adopters that some of the essential attributes of the platform will be integrated and supported over time. It is also critical that the open architecture supports emerging innovations that advance the platform ecosystem. The VOLTTRON open architecture has been developed collaboratively to meet these needs and continues to evolve through the mechanisms developed for technology transfer, including active industry partnerships and bi-weekly "Office Hours" and online support.[12]

Although the open architecture and continued support provide the foundation for innovative growth by a large number of participants, an alternative path to market could also come in the form of a "top-down" platform implementation by a single large firm (e.g., GE, IBM, etc.) that brings with it a pre-established community of users. In such cases, it is possible that the platform could still remain open, but the implementing firm could dictate certain rules of governance and standards relatively efficiently; however, it is possible that grass-roots app development may be limited or restricted if this business model were to gain market acceptance. It is also possible for a single innovation to drive the market in a certain direction, even if the firm is not large and well established. For example, the Nest thermostat in the residential market was a single innovation that achieved wide acceptance and drove the rest of the thermostat market toward offering more innovative hardware and software features.

The initial investment in the open VOLTTRON platform does not preclude any of these pathways. However, by providing the open architecture and collaborative support and by investing in pilot programs that help establish the platform-adoption/app-developer ecosystem for multiple buildings applications, the approach at least ensures the possibility that a more organic (i.e., bottom-up) pathway toward the market, involving multiple app developers and platform adopters, could exist. This more organic approach would also leave the door open for more customization to the end-users' needs, which could be particularly useful to the currently under-served SMCBs.

The pathway to market depends on how well the VOLTTRON platform meets the challenges of managing the delicate balance between app developers' autonomy to freely innovate and ensuring that apps seamlessly interoperate within the platform. It must simultaneously adjust architecture and governance of a platform for an app to maintain alignment between them.

5.1 Market Drivers

Before a transactive open platform could be accepted and successful in a given market, a number of basic conditions should be met including digitization of building equipment and systems. In addition, the

[12] For more information, see the Wiki site for VOLTTRON at https://github.com/VOLTTRON/volttron/wiki/Office-Hours-Agenda..

SMCB market will be able to benefit from an open platform as systems become more specialized and complex. They will be able to keep adoption costs down with help from cheap and fast wireless Internet data networks and cloud-based systems. These and other factors will drive and shape the market for an open transactive platform in the SMCB sector.

5.1.1 Building Automation Trends in Small- and Medium-Sized Commercial Buildings

Based on input from key stakeholders as described in 2015 market assessment on the topic of transactive platforms performed by Navigant Consulting (Navigant 2015), the current and predicted state of building automation presents both challenges and opportunities with regard to the market uptake of an open VOLTTRON platform. Trends toward more automation suggest a potentially receptive consumer base for an open platform; however, stakeholders identified compatibility issues with existing systems as one of the key challenges to integrating the VOLTTRON platform in the market.

While some form of BAS adoption is standard for larger buildings, SMCBs are less likely to have a BAS in place. Moreover, those buildings that do have a BAS often are not operating it to its full potential, as specialized training and dedicated staff are typically needed. However, there is a growing trend toward the implementation of building controls in smaller buildings, with a goal of better managing energy expenses. This is especially true of enterprises with large portfolios of SMCBs, such as banking, big box retail, food sales (grocery), and food service (convenience stores and chain restaurants) establishments. There may be other systems including security and fire protection that may be part of a larger suite of tools (Navigant 2015).

Historically, building controls have been too complex and too expensive for installation in smaller buildings. In addition, these smaller buildings typically do not have employees with the time and expertise to manage building operations, especially in terms of optimizing energy use, scheduling, etc.; yet, these customers have been receptive to solutions that include items like networked thermostats and lighting controls that also come with building energy management packages. Such a package often allows the customers to easily manage equipment schedules and optimization routines across multiple buildings.

Open Protocol

Demand from building owners and operators has spurred the development of open protocols. Today, customers are migrating to control systems with open protocols like BACnet and LonWorks. As controller equipment is replaced over time, almost all new equipment will be compatible with at least one, if not several, open protocols, further accelerating the proliferation of open protocols in the building stock. The primary advantage is flexibility (Navigant 2015).

Open protocols mean that customers are no longer tied to one vendor; rather, they can select from a number of equipment providers as long as the equipment supports the protocol used within the building. Open networks are also another step toward systems integration. If HVAC and lighting equipment are using the same language, then it is relatively simple to have them and share information (Navigant 2015).

Cloud Computing and Internet of Things

Cloud computing and the Internet of Things (IoT) are major tech industry trends that apply in facilities and energy management by way of building automation and control systems. More and more building services operate in the cloud, which has appeal to capital-constrained customers who have avoided improvements to legacy systems or investment in new traditional control and automation. Cloud-based systems provide ease of integration by eliminating the need for dedicated onsite hardware. They also ease process for updating software and offer the ability to scale to other facilities and add functionality. This model has specifically opened new opportunities with smaller buildings, and this trend bodes well for VOLTTRON to the extent that VOLTTRON supports and facilitates these cloud-based systems (Navigant 2015).

An IoT-enabled building can leverage IT for business improvements and use data, communication, and analytics to make informed decisions related to system performance. IoT is beginning to permeate the buildings sector, including SMCBs. By leveraging innovations from the broader IoT landscape, the IoT-based system helps building energy service providers and building end-users make data-driven decisions to improve both commercial building performance and business operations housed in the building (Talon 2016).

5.1.2 Utility Programs and Incentives

Most energy utilities covering the vast majority of commercial buildings offer at least custom incentives that can include an energy management system. However, in terms of complexity, the program requirements vary by region. There has been an increase in utility energy-efficiency programs targeting SMCBs, where at least 20 states have utility programs that explicitly target this sector.[13] Programs include energy audits, financial assistance and grant programs for energy upgrades, direct equipment installation programs, and education and training programs. In addition, there are over 92 energy-efficiency programs identified throughout the United States that incentivize RTU upgrades and retrofits.[14]

Historically BASs were of interest to utilities primarily through energy-efficiency programs. However, with the growing business of demand-response programs, onsite generation technologies and the desire to be more customer service oriented, many utilities are looking at increasing their support for, and integration with, building management systems in customer facilities.

Although one important goal of DOE's grid-to-building efforts would include utility acceptance and support for transactive energy networks, previous research efforts in this area suggest that a long-term horizon would be applicable to this goal.[15] In the shorter term, however, as more and more intelligent devices are deployed within buildings, the opportunities for automation will increase opportunities for an open platform, such as VOLTTRON, to help integrate and automate systems in a manner to effectively take advantage of utility energy efficiency and demand-response programs.

5.1.3 Other Market Drivers and Trends in Small- and Medium-Sized Commercial Buildings

The factors that drive decision-making in the SMCB sector will depend on the individual ownership structure and building activities and purposes. National and regional chains have come to dominate the enclosed and strip-mall retail outlets as well as many of the food-service and food sales buildings; thus, much of the decision-making related to facility and energy management for these building types comes at a corporate level. Similarly, decisions about energy management and improvements for education

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[13] See https://www.sba.gov/content/state-and-local-energy-efficiency-programs and http://www.dsireusa.org/.
[14] Advanced RTU Campaign database of HVAC RTU Incentives as of December 4, 2014. Available online (February 2016) at http://www.advancedrtu.org/financial-resources.html.
[15] See, for example, Figure 4, "Stages of Adoption of Transactive Operations for Industry," (GridWise Transactive Energy Framework Version 1.0, January 2015, The GridWise Architecture Council. http://www.gridwiseac.org/pdfs/te_framework_report_pnnl-22946.pdf.

buildings are often made by a centralized governing body and are often budget-constrained decisions; however, more school districts and colleges are implementing guidance and requirements to improve the energy management of facilities. Past surveys (e.g., CBECS/EIA 2003) suggest that about 45% of office buildings are owned by either property management companies or corporations and just over 30% are owned by individual owners. Many of these buildings do not have a designated energy manager, but instead have a facility manager who is in charge of multiple facility functions. In general, the SMCB sector has fewer resources to invest in energy improvements than their larger building counterparts; however, management of these facilities is often more flexible, and ownership can make decisions more quickly than large building owners/managers.

Based on recent market surveys,[16] SMCB owners and energy managers are primarily driven by the cost savings provided by building energy services. The size of portfolio being managed is important in assessing the opportunity for building automation and control service adoption. Once a portfolio owner sees they can have a multi-building view of energy use, including ways to conserve energy and reduce costs, they are more likely to adopt across the portfolio. With regard to building automation, SMCB owners and building managers required systems with simple interfaces and customization to the information needed by the particular building owner. Services such as measurement and verification were ranked highest among energy service needs. HVAC services, on the other hand, were not ranked very high with this customer base, suggesting that integrated systems and packages may be more effective at gaining the attention of small and medium building owners.

The challenges in reaching this market sector are significant; however, in addition to some of the favorable trends in building automation and utility incentive programs, there are some other noteworthy trends that work in favor of VOLTTRON market acceptance and adoption, including:

- *Green building labeling* programs targeting both new buildings and retrofits, such as LEED (Leadership in Energy and Environmental Design) and Energy Star labels, are increasing in popularity for buildings of all sizes. To the degree that VOLTTRON helps facilitate metering, monitoring, automation, control, and commissioning of a building, it can help comply with certain elements of the LEED, Energy Star, and other building rating criteria.
- An increasing number of *smart meter installations* makes it easier for utilities and municipalities to reach and assess building energy in smaller commercial buildings.[17] By the end of 2014, Energy Information Administration reported that over 58 million advanced electric smart meters installations, with over 6.5 million smart meters installed in commercial buildings around the United States.[18]

[16] See presentation entitled, "Energy Efficiency, Demand Response, and VOLTTRON," presented at the VOLTTRON stakeholder Workshop on July 24, 2015. Available online at http://energy.gov/sites/prod/files/2015/08/f25/09.%20Volttron%20Conference%20Presentation%20%28Sipe%29%20%281%29.pdf.
[17] "Engaging the Small and Mid-sized Business (SMB) Marketplace," Webinar presentation by Duke Power and Schneider Electric. Available online at https://event.webcasts.com/viewer/event.jsp?ei=1050930
[18] http://www.eia.gov/tools/faqs/faq.cfm?id=108&t=3.

- In addition to DOE's R&D efforts to bolster small commercial building energy efficiency,[19] there are some *large-scale comprehensive initiatives* in this area including Duke Energy's "Engaging with the Small & Mid-Sized Business Marketplace"[20] in partnership with Schneider Electric. Initial feedback from participants of this program has been very positive and businesses have been very receptive to the attention they are getting from the utility. This notoriously hard-to-reach sector appears to be receptive when utility programs are focused on them.
- Some *codes*, *mandates*, and *municipal guidance* are directing SMCBs toward energy-efficient retrofits, including automation, controls, and commissioning.[21] Woven throughout the code are specific requirements for controls. Optimized controls are now required for HVAC systems and lighting controls (for interior, exterior, and parking structure lighting) as well as control over certain plug loads. While the standards do not explicitly require the use of systems integration or an "intelligent building system," it does have much more extensive controls requirements. The use of an integrated approach is likely to both be more cost effective and provide the required performance of this more stringent code. These building codes have had an influence on the overall market uptake of commissioning and monitoring service; thus, VOLTTRON acceptance could be influenced as well depending on the degree to which an open platform helps facilitate and reduce the cost of compliance with these code requirements.

5.2 Opportunities

There is a diverse and competitive landscape in the emerging "connected buildings" market, which provides opportunity for innovative companies to provide solutions. Large incumbent players that have traditionally supported buildings and building services can bring domain expertise to the field, but there are additional opportunities for partnerships that leverage cutting-edge technologies from new entrants, particularly those targeting SMCBs (Talon 2016). The overall market outlook for building automation services, including advanced sensors, electricity smart meters, and building energy management service software and associated services is expected to grow significantly over the next 5 years, with an estimated compound annual growth rate of 15.9% globally (Navigant 2015). As this market evolves, building energy service providers can install VOLTTRON-based network-secure platforms that scale to support growing opportunities for cost savings and efficiency in smaller buildings that lack traditional controls and automation.

Although opportunities in this dynamic environment exist throughout the United States, specific market entry opportunities will likely be greatest in areas where high energy costs and ample commercial building utility incentives exist. These areas would include California and the Northeast region, both of which include large-scale utility programs that are moving toward a different model of customer engagement requiring quality data that VOLTTRON-based applications could offer.

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[19] See for example, Advanced RTU Campaign (http://www.advancedrtu.org/) and 2016 Funding Opportunity – Small-Medium Commercial Buildings. Available online at http://energy.gov/eere/buildings/articles/funding-opportunity-small-medium-commercial-buildings.

[20] "Engaging the Small and Mid-sized Business (SMB) Marketplace," Webinar presentation by Duke Power and Schneider Electric. Available online at https://event.webcasts.com/viewer/event.jsp?ei=1050930.

[21] The International Energy Conservation Code requires commissioning of HVAC equipment, lighting controls, and HVAC control systems for projects with capacities greater than 480,000 Btu/h for cooling capacity and 600,000 Btu/h for heating capacity.[21] Similarly, ASHRAE Standard 90.1-2010 includes a commissioning requirement based on total building floor area, where commissioning is required for buildings over 50,000-ft^2.

The state of building energy management systems in SMCBs offers opportunities for building energy services in this sector. Stakeholder surveys[22] suggest that small commercial building operators and service providers have a good understanding of the potential benefits of building automation, integration, and control; however, many customers seem generally unhappy with the products on the market due to cost, complexity of use, and the sparse and sometimes irrelevant analysis offered by these systems. A VOLTTRON-based software option that offers clear and simple insight into the operations and energy usage of their system could differentiate itself in this market. For buildings that already have BASs in place, the VOLTTRON-based system should be able to work with it to offer more tailored and expanded services cost effectively to owners. Although VOLTTRON development will likely be aligned with trends in building automation, the successful deployment of an open platform in this sector could also potentially facilitate overall growth in building automation and integration services.

Overall, the applications that could be supported by a VOLTTRON platform and are the most desired by SMCB owners include easy-to-read energy dashboards providing behavioral and educational energy-saving suggestions, utility bill management services, benchmarking, and fault detection and diagnostics (Navigant 2015). Measurement and verification services (M&V) are also key services for this sector, especially if they are designed to assist in meeting green labeling or other program requirements and help provide the building owners with insights into efficiency and operational enhancements that improve the bottom line (Talon 2016). The increased flexibility of the VOLTTRON system to manage a wider variety of energy using equipment and offer a larger number of options and customization for managing energy usage and demand should help expand the market for the open VOLTTRON platform to small and medium commercial buildings.

Small- and medium-sized commercial building owners are extremely bottom-line driven and can sometimes be more engaged and responsive to building occupant needs. As a result, some building energy service companies have found that phased approaches to implementing intelligent systems work well with SMCBs, where simple tools might be introduced to help make sense of some of the metered data, for example, enabling building owners to make informed decisions about which intelligent apps and systems are appropriate for their buildings. Because some of the more successful implementations involve engagement with the end-user building occupants, apps and tools that help facilitate this engagement can be of value in the SMCB sector (Talon et al. 2016).

To summarize, the successful implementation of an open platform should take advantage of VOLTTRON's comparative benefits and attributes as a platform in the SMCB sector, keeping an eye toward trends and opportunities such as utility incentive programs and areas where energy costs are high (and where these two factors intersect). Energy service providers and app developers can use the VOLTTRON platform's comparative benefits and attributes to address the specific needs and demands of SMCBs keeping in mind the most recent trends and market drivers in this sector, such as the move toward cloud-based computing, open and interoperable platforms, simple user-friendly interfaces, packaged/integrated products, M&V, and services that make the most of non-energy benefits such as fault detection and diagnostics and security.

[22] See presentation entitled, "Energy Efficiency, Demand Response, and VOLTTRON," presented at the VOLTTRON Stakeholder Workshop on July 24, 2015. Available online at http://energy.gov/sites/prod/files/2015/08/f25/09.%20Volttron%20Conference%20Presentation%20%28Sipe%29%20%281%29.pdf.

6.0 Addressing Barriers

Although the VOLTTRON platform is designed to reduce and eliminate some of the barriers encountered by commercial building owners in their move toward more intelligent and automated management and control systems, this technology still faces a number of barriers inherent to working with buildings and building management. In addition, there are a number of technical barriers that will be encountered related to the deployment of software platforms and automation in the SMCB sector.

6.1 Barriers to Market Entry

With regard to deployment and market acceptance of the VOLTTRON platform in the SMCB sector, it will face many of the same technical and market barriers that are inherent for most energy services in this sector. These would include:

- *System Cost Requirements (first costs)*: The first cost requirements are very rigid for SMCBs due to limited cash and capital investment budgets.
- *Integration Costs for Existing Buildings*: Although significant savings can be realized from automating and integrating multiple systems within a building, the reality of implementation is often complicated with costly retrofit needs. Properties can often be complicated with mixed use and atypical functions that do not easily integrate.
- *Short Payback Thresholds (risk averse)*: The threat of loss is too great if the promised returns do not materialize; thus, SMCB owners require very quick simple paybacks.
- *Limited Staffing and Expertise Dedicated to Building Energy Management*: Many newer technologies such as automated controls and software platforms require at least some level of operations management beyond what is available to owners. Hiring building energy managers or retraining existing property staff might be too expensive for owners/managers of small buildings to justify. Even if technical expertise is not required to manage the system, smaller commercial building owners would reasonably presume that there is some level of expertise needed to evaluate whether or not these newer technologies and systems are needed in a given building.
- *Value Proposition (savings validation)*: The technology and corresponding energy savings and financial risk analysis are complex and unfamiliar to the owners of small properties, especially as many owners in this group have no readily available and impartial third-party advisers to advise them.
- *Validation of Non-Energy Benefits*: Many of the non-energy benefits associated with energy systems, such as improved building comfort and air quality, are neither well documented nor communicated to building owners.
- *Commercial Building Lease Terms*: Commercial leasing terms often do not work in favor of energy system upgrades because of landlord-tenant split incentives, particularly if the technology being considered is novel in any manner.

In addition, there are technical and market barriers inherent for any new platform and the move toward intelligent, connected buildings. These barriers are briefly described below.

- *Legacy Systems and Integration*: Often service providers have to integrate with legacy systems or existing controls, as well as other system integration companies and utilities. Currently, little incentive exists for existing players to work with service providers. In addition, smaller commercial buildings often lack distributed control systems and may require rigid site-level controls that are not easy to retrofit.

- *Cyber-Security and Interoperability Certifications*: When vendor certification is needed, the process could be too expensive for a startup company. IT and cyber-security concerns and requirements prohibit fast projects, rapidly changing technology, and changing vendors quickly.
- *Demonstrating the Value*: Demonstrating the value of transactive capabilities to utilities, regulators, and building owners is a challenging task.
- *Utility Acceptance*: Lack of acceptance, specifications, and support of transactive controls and platforms could hinder end-users' acceptance of an open platform.

6.2 Risks Associated with VOLTTRON Adoption

There are inherent risks that the platform adopter and app developer take on when moving to a new platform. To evaluate these risks with respect to the VOLTTRON platform, Transformative Wave, under contract to PNNL, conducted an informal survey of their customers who were both platform adopters and app developers related to risk factors in various categories (Transformative Wave 2015). General risk factors related to transactive platforms also were reviewed based on a market assessment of the topic (Navigant 2015). Overall, the risks associated with the adoption of VOLTTRON are relatively low, in part because many of the risk mitigation efforts were included during its development (see Section 6.3).

- *Alternative Platforms*: One risk associated with platform adoption is that an alternative platform may end up dominating the field, which could potentially result in incompatibilities with the alternative more dominant platform. Although there are many platforms available to support building systems and automation, there are not many companies currently offering a comprehensive controls solution for the SMCB market. However, the market for larger buildings is quite robust and many companies have been entering this market with innovative software solutions. Any one of these firms may see this as a new market opportunity, which could impact future adoption decisions.
- *Personnel Support*: While some companies may have a depth of understanding among software design staff to support platform adoptions and improvements, others may require investment in new staff and further developing these capabilities before successfully adopting or developing applications for a new platform. Although the skill set needed should be available in the marketplace, the time necessary to bring them up to speed on the software may delay implementation of the product or improvements after deployment.
- *Cost Overruns*: Although VOLTTRON R&D efforts have sought to mitigate risks associated with implementation costs, the risk of cost overruns is inherent with the implementation of any new technology. However, case study participants have provided favorable feedback regarding the implementation costs, suggesting that this could be considered a low-risk factor.
- *Technology Adoption Risks*: Another inherent risk factor with technology adoption is that the adopter will encounter technical difficulties and the possibility that the technology simply will not work for the adopter for any number of reasons. In addition, because VOLTTRON is still in the development stage, there is a risk that continued support and funding for development could cease in the future. To help mitigate this risk, a number of technical guides and support options have been made available to users and potential users. In addition, the results and technical field notes of the demonstration pilots and testing of VOLTTRON have been made available to the public.

6.3 Addressing Barriers and Mitigating Risks

Many of the key drivers behind the impetus for developing the VOLTTRON platform focused on the potential risks associated with technology adoption and current market and technical barriers faced by SMCB end-users and the energy service companies that serve this sector. As a result, attributes such as security and resource management played a large role in driving the approach and architecture of the platform. Security is built into the platform and not "bolted on" as is frequently the case in other platforms. This is especially important to support low-cost implementation, maintenance, and app development on the platform. Likewise, because VOLTTRON has always been targeted at small computing devices, the platform itself has been designed to use minimal resources, which allows the platform to run on low-priced commodity boards, which greatly reduces hardware costs for deployment and makes it more cost effective for small and medium building use cases.

To address potential barriers and risks associated when working with legacy systems and other platforms, VOLTTRON has been designed to be open and flexible so it can be used with a wide variety of devices, protocols, and other platforms. Through the use of translation V-Agents, VOLTTRON can enable communication and integration with other platforms that may work with a different ecosystem of devices and applications. This integration allows each platform to play to its strengths and enrich the solution space by avoiding "either/or" decisions. With regard to legacy systems, VOLTTRON isolates the details of communicating with devices from the rest of the actors in the platform. This allows app writers to work with data coming from the message bus without having to worry about the details of where it came from. This design can ease integration of legacy systems by hiding any complexities of interacting with a device. The device can participate in the VOLTTRON platform if it can be made to interact through existing input/output capabilities or via retrofitting.

In addition, the VOLTTRON development team has attempted to reduce a variety of costs (e.g., implementation, maintenance, app development, staffing limitations, etc.) associated with platform adoption and use by including a number of support and technical assistance options. For example, the VOLTTRON development team holds regular "Office Hours" during which members of the team are available to discuss new features and plans as well as answer questions from the user community. This has been a very active support network, where technical support staff field questions range from the basics of how to get started with the platform, how to build V-Agents, to more complicated questions about the code. The VOLTTRON user community spans a wide range of experience in the domains of buildings and computer science. For some users, this is their first foray into working in Linux and programming in Python. The VOLTTRON team also has provided a detailed user guide, a wiki, and white papers that provide additional resources to those working with the platform. The user guide provides step-by-step instructions for getting started while the wiki contains details of various components of the platform. The white papers provide background and context to the project as well as in-depth discussion of topics such as security.

Table 6.1 provides a summary list of the barriers to market entry and describes how these barriers are either currently being addressed or possible approaches to addressing the barrier. It also identifies some of the specific market stakeholders and/or pilots and case studies that help reach the appropriate core customers to effectively address the barrier.

Table 6.1. Addressing Barriers

Barriers	Addressing Barriers	Pathways to Market
Cost	VOLTTRON has always been targeted at small computing devices, and the platform itself has been designed to use minimal resources. This allows VOLTTRON to run on low-priced commodity boards ($35 or less), which greatly reduces hardware costs for deployment and makes it more cost effective for SMCB cases. These cost-reducing features are being demonstrated in ongoing case studies.	Pilots like BEMOSS that focus on small building applications and cost need to find a way to communicate findings to core customers and end-users. Consider cost study and testing to examine costs to maintain platform over time.
Payback and Risk Aversion	Through its technical assistance efforts, the VOLTTRON team has made great efforts to mitigate risks associated with implementation of the platform. The VOLTTRON development team holds regular “Office Hours” during which members of the team are available to discuss new features and plans as well as answer questions from the user community. For the consumer, these “Office Hours” help reduce initial and ongoing costs and help consumers realize the associated benefits with adopting the VOLTTRON platform.	Continued support of online technical assistance and integration of lessons-learned. Pilot and case studies can also address risk aversion when results and lessons-learned are properly documented.
Building Staff Limitations	VOLTTRON also has developed a detailed user guide, a wiki, and white papers that provide additional resources to those working with the platform. The user guide provides step-by-step instructions for getting started while the wiki contains details of various components of the platform.	Determine what types of information building facility managers want and need to help with decision-making. Develop “Best Practice” guide for building owners, facility management, and IT staff focused on small buildings.
Value Proposition	DOE has partnered with multiple commercial and academic users (e.g., Transformative Wave Technologies, Virginia Tech, Drexel University, Emerson Climate Technologies, and Quality Logic) to carry out field studies and testing of the VOLTTRON platform to validate benefits.	Need to communicate results of case studies to the app development community and commercial building end-users. DOE VOLTTRON outreach meetings, such as those conducted at Virginia Tech and Drexel University with the user community, are ideal venues for this activity.
Valuing Non-Energy Benefits	End-users often are driven by non-energy benefits such as building comfort, maintenance and diagnostic capabilities, and cyber-security. Case studies should be documenting these non-energy benefits.	Document non-energy benefits associated with VOLTTRON as shown in case studies and communicate results in appropriate venues, including DOE outreach meetings and selected conferences.
Commercial Lease Terms	No specific strategy identified. If the demand for “green” building labels and “intelligent” building systems grow and becomes more standard, these measures can more easily be addressed as part of leasing arrangements.	

Barriers	Addressing Barriers	Pathways to Market
Legacy Systems and Integration	VOLTTRON has been designed to isolate the details of communicating with devices from the rest of the actors in the platform. This allows app developers to work with data coming from the message bus without having to worry about the details of its origin. This design can ease integration of legacy systems by hiding any complexities of interacting with a device. If the device can be made to interact (through existing input/output or via retrofit), it can participate in the platform.	Continue development in this area and highlight these features to user community.
Cyber-Security	Security is built into the VOLTTRON platform. Cyber-security specialists on the development team ensure that every feature and facet of the platform keeps security in mind. VOLTTRON's security features are considered a key strength by stakeholders.	Need to highlight the security strengths of VOLTTRON through the Information Technology network. Also via outreach inherent in the Building Technology Office's ongoing Cyber-security and Buildings Project with Federal Energy Management Program. Develop "Best Practice" guides for implementing secure systems.
Interoperability	VOLTTRON has been designed to be open and flexible to allow it to work with a wide variety of devices, protocols, and other platforms. Through the use of translation V-Agents, VOLTTRON can enable communication and integration with other platforms which may work with a different ecosystem of devices and applications. This integration allows each platform to play to its strengths and enrich the solution space by avoiding "either/or" decisions.	Continue development in this area. Consider suggestions for easy interoperability checks for application developers. Document lessons-learned online for users.
Utility Acceptance	Although VOLTTRON has the transactive capabilities to connect with the grid and support demand response programs, these features need to be demonstrated in the field. Utility pilot programs demonstrating these capabilities would be beneficial.	Pursue utility pilot demonstrations.

7.0 "How-to" Tech-to-Market Best Practice Guidance

This chapter provides "How-to" tech-to-market best practice guidance for interested stakeholders and platform participants in the SMCB sector. It is designed to provide these market participants high-level guidance to help plan for and implement an open VOLTTRON platform approach and strategy into building energy service business models. This guidance draws from previous sections of this report. Figure 7.1 illustrates the general "how-to" process.

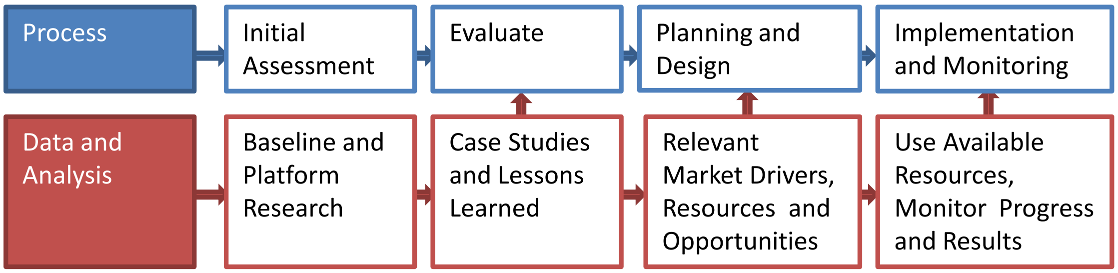

Figure 7.1. VOLTTRON Implementation Process

7.1 Initial Assessment

An initial assessment of the potential value proposition of the VOLTTRON open platform should be completed with respect to the core capabilities and goals of the platform adopter and app developer (i.e., building energy service provider). Would an open platform, such as VOLTTRON, add value to services provided and complement the current business model? Consider the potential benefits of the open platform systems as discussed in Section 4.1 and summarized in Table 4.1 of this report. These open platform benefits should include:

- Cost reductions in service delivery
- Risk distribution
- Innovation on core capabilities
- Greater functionality
- Low-cost app development
- Improved market access for application and services.

The open platform should also enable benefits to the end-user in terms of: 1) better customization to end-user needs, 2) faster innovation and better networks for end-user, and 3) lower search costs and transaction costs for end-users.

Once a determination is made that an open platform could potentially add value to the services and applications provided by the business, then a more in-depth assessment should be made of the specific attributes of VOLTTRON, in comparison to alternative platforms, to determine whether these attributes meet the specifications of the relevant business model. A preliminary assessment of VOLTTRON's attributes is discussed in Section 4.2 and summarized, as of the date of this report, in Table 4.2. The VOLTTRON user guide (Lutes et al. 2012), references material, and a description of all system requirements and is available online at VOLTTRON's "wiki" page.[23]

[23] See Github site: https://github.com/VOLTTRON/volttron/wiki.

7.2 Evaluation

A number of case studies and field tests that specifically examine VOLTTRON's performance and capabilities in the SMCB sector have been completed and should inform any party interested in the adoption of the VOLTTRON platform. Potential users should carefully review these case studies and see which may apply to their particular situation. They may also want to contact PNNL directly for more insights at VOLTTRON@pnnl.gov. These case studies are described in Section 4.2, and in more detail in Appendix A and Appendix B of this report. Case studies highlight VOLTTRON's support of the following SMCB applications:

- RTU energy-efficiency services and control
- HVAC device controllers
- BAS interaction and integration
- Building energy management systems tailored for SMCBs
- Refrigeration defrost control
- Lighting controls
- Plug-load controls
- Lighting diagnostics
- AFDD for air-handling units and variable air volume systems
- Demand response
- Transactive node control.

The VOLTTRON-based applications were demonstrated in a number of different types of buildings including offices, mercantile and service-oriented buildings, supermarkets, restaurants, and buildings that support educational services and public assembly (e.g., classrooms, libraries, gymnasiums, etc.).

7.3 Planning and Design

As discussed in Chapter 5 of this report, there are a number of market drivers and opportunities that should be considered as part of any planning and program/product design targeting the SMCB sector. The market outlook for building automation services, including advanced sensors, electricity smart meters, and building energy management service software and associated services is expected to grow significantly over the next 5 years, with an estimated compound annual growth rate of 15.9%, globally (Navigant 2015). As this market evolves, there will be greater opportunity for solution providers serving the SMCBs to leverage buildings and integrate building energy and energy-efficiency services, dynamic grid integration, and distributed energy resources.

Interested parties should assess market drivers and opportunities, including those in Chapter 5, and develop an approach for leveraging those via VOLTTRON. A specific path forward for designing an application should be developed that considers trends in building automation, particularly with regard to cloud computing and connectivity (e.g., IoT) and open protocol development. In addition, utility incentives and other program drivers, such as building energy labeling, codes and standards, and smart-grid/smart-city initiatives, should be monitored for potential opportunities in the SMCB sector.[24]

Because the SMCB sector has some unique drivers, dynamics, and constraints, building energy solution providers should pay close attention to these end-user needs, including the need for products with user-friendly interfaces that are low-cost and secure applications. SMCB owners and occupants are also looking for applications with M&V capabilities that make the most of non-energy benefits such as fault detection and diagnostics.

7.4 Implementation and Monitoring

Successful implementation of an open platform should take advantage of VOLTTRON's comparative benefits and attributes as a platform in the SMCB sector, maintaining an awareness of opportunities such as utility incentive programs and areas where energy costs are high. Energy service providers and app developers can use the VOLTTRON platform's comparative benefits and attributes to address the specific needs and demands of SMCBs keeping in mind the most recent trends and market drivers in this sector, such as the move toward cloud-based computing, open and interoperable platforms, and simple user-friendly interfaces.

The VOLTTRON development team has developed a number of guidance documents and resources for the VOLTTRON implementer, whether they are new to VOLTTRON and the open platform concept or experts in the field.[25] Any implementation should take full advantage of these online resources. In addition, the VOLTTRON development team holds regular "Office Hours" during which members of the team are available to discuss new features and plans as well as answer questions from the user community. The VOLTTRON development team welcomes feedback and contributions to code development, which is facilitated through its GitHub website.

An implementation of new apps and platforms should be evaluated and monitored to ensure that expected benefits are realized. Technical support resources and the user community can help resolve issues that are encountered during implementation and operation of a VOLTTRON-based implementation. Continuous monitoring and adjustment of services is enabled through VOLTTRON's flexibility and its ability to be extensible and evolve in response to dynamic needs of the building community.

[24] One resource is the Database of State Incentives for Renewables & Efficiency, which is a comprehensive source of information on incentives and policies that support renewable energy and energy efficiency in the United States. Available at http://www.dsireusa.org/.

[25] See VOLTTRON GitHub site at https://github.com/VOLTTRON/ for more information.

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Appendix A

Case Study Participants

Appendix A

Study Participants

Transformative Wave Technologies was selected in the early stages of VOLTTRON™ development as a private sector cost-sharing partner with Pacific Northwest National Laboratory (PNNL) to build VOLTTRON-based solutions for the small commercial building market, where cost is especially critical. Transformative Wave Technologies has chosen to deploy a VOLTTRON-based product to lower their cost of delivery of energy-efficiency services by 50% and to create multiple value streams (grid services) with the same technology.

Virginia Tech became interested in VOLTTRON when it was demonstrated at the 12th International Conference on Autonomous Agents and Multiagent Systems in 2013, and identified it as an excellent source for a U.S. Department of Energy (DOE) project to develop a small building management service. They had developed capabilities for the service but had no integrating framework until they adopted the PNNL-developed VOLTTRON. The result, still under development, is the Building Energy Management Open Source Software, or BEMOSS, that once deployed will deliver energy-efficiency services in the small- and medium-sized commercial building sector. With progress to date on BEMOSS, Virginia Tech has been able to successfully compete for follow-on funding from DOE.

Emerson Climate Technologies will begin using VOLTTRON in FY 2016 to expand their energy services offering to deliver energy-efficiency and grid services at convenience stores and supermarkets. Emerson currently provides some energy services, but with VOLTTRON, they now will be able to enhance these services by adding automated fault detection and diagnostics as well as automated energy demand-response capabilities to their customers.

Quality Logic, a company that provides quality assurance test tools for smart energy markets, had begun building its own application but abandoned that effort once VOLTTRON, a no-cost and low-human-resource solution, was introduced. They previously used VOLTTRON to develop a demand response-specific version under the PNNL-led Pacific Northwest Smart Grid Demonstration Project, which concluded early 2015.

Drexel University has secured the technology to help further develop a VOLTTRON-compatible automated fault detection and diagnostics tool that integrates statistical process control, machine learning, and rule-based methods to reduce energy consumption. The university recently received funding from DOE to continue development of the tool based on their use of VOLTTRON.

In addition, three national laboratories—Oak Ridge, Lawrence Berkeley, and the National Renewable Energy Laboratory—have licensed the enhanced version of VOLTTRON to capitalize on its full capabilities as a transactional reference platform for developing energy-efficiency and grid services applications that can be transferred to the marketplace.

Through transfer of this no-cost, energy-efficiency and grid tool by PNNL engineers, software developers, and commercialization staff, PNNL has provided academic, commercial, and national laboratory institutions a significantly tested tool to address increasingly complex electricity infrastructure with scientific advances and commercial product offerings through increased energy efficiency, improved grid reliability, and security.

Appendix B

Summary of Case Studies and Lab/Field Testing

Appendix B

Summary of Case Studies and Lab/Field Testing

Study Title	Year/ Time Period	Type of Study	Host	Principal Investigators	Sponsors	Focus of Study	Application (e.g., HVAC, Refrigeration, etc.)	End-User/ Building Type	Location (Utility Region)	Key Outcomes/ Notes	Links to Presentations/ Sources
Automated Fault Detection and Diagnosis for AHU-VAV Systems	2015	Field Study	Drexel University	Drexel	EERE -- CBEI	VOLTTRON-based platform to integrate fault detection and diagnostic systems for automatic air handler-variable air volume systems. Attempting to demonstrate non-intrusive retrofit strategy that will not impact comfort or existing control strategy.	HVAC	Four commercial buildings (featured output for 74,000-ft^2 commercial building mix office and classroom with built up chiller/steam)	Philadelphia PA (PECO)	Demonstrated potential effectiveness for all types of fault detection: dampers, valves, fans, sensors, controls, etc. Ongoing, continuing automated fault detection and diagnostic demonstration. Plan to develop web-based automated fault detection and diagnostic interface and integrate active diagnostics. Used VOLTTRON because it was open-source, many platforms services already developed and available, integration with other "agents" was via single point of contact for device, it was secure and flexible (e.g., cloud-based application and local application could work together)	http://energy.gov/sites/prod/files/2015/08/f25/12.%202015-07-23_Drexel_Voltron_wkshp%20%28Wen%29.pdf
BEMOSS (Building Energy Management Open Source Software)	2015-	Case Study/Lab Testing	Virginia Tech	Virginia Tech (with 22 organizations on advisory committee)	EERE	VOLTTRON-based (i.e., VOLTTRON was used as platform to host BEMOSS) monitoring and controlling system engineered to improve sensing and control of equipment in small- and medium-sized commercial buildings.	HVAC, Lighting, BEMS/BAS, plug loads	Small- and medium-sized commercial (tested in 25,000-ft^2 mixed classroom building)	Arlington, Virginia (not applicable)	Initial testing suggest that BEMOSS can improve energy efficiency and facilitate demand response implementation in buildings. VOLTTORN applicable to small to medium buildings in that it could be applied to HVAC typical to small to medium building, lighting load controllers and plug-load controllers. Low-cost solutions using conventional embedded devices (e.g., BeagleBoard, Raspberry Pi, Android, PandaBoard, etc.)	http://energy.gov/sites/prod/files/2015/08/f25/08.%20BEMOSS_VOLTTRON_meeting_V3.pdf

Study Title	Year/ Time Period	Type of Study	Host	Principal Investigators	Sponsors	Focus of Study	Application (e.g., HVAC, Refrigeration, etc.)	End-User/ Building Type	Location (Utility Region)	Key Outcomes/ Notes	Links to Presentations/ Sources
Energy efficiency and Grid Services for C Stores & Supermarkets	2015	Lab Testing	Emerson Climate Tech. Retail Solutions	Emerson and ORNL	EERE	Featured: Demand Defrost App Utilized Platform for Development. Also, identified other applications in Food Sales sector where VOLTTRON could be used to develop applications including: HVAC fault detection and diagnosis (FDD), Load shaping, demand frost, and demand response. It could be used in a retrofit application as well as new sites.	Refrigeration	Refrigerated display cases in supermarket (where low-temp cases use 720 kwh/month/ case to defrost.	Sydney, OH (not applicable)	Targeted problem: frost formation on evaporator coils that decreases operational efficiency. Solution tested: Develop algorithm to perform defrost-on-demand using VOLTTRON Platform *with* Emerson E2 Controller. Demonstrated up to 75% reduction in defrost energy. VOLTTRON provides a consistent platform for application development and functionality testing. Considering other applications related to HVAC FDD, load shaping, and demand response.	http://energy.gov/sites/prod/files/2015/08/f25/17.%20Emerson_VolttronTechnicalConferenceJuly2015%28Wallace%29.pdf
Scalability Analysis of VOLTTRON Platform	2015	Simulation	Oak Ridge National Laboratory (ORNL)	ORNL, PNNL	EERE	Develop simulation-based deployment environment for testing VOLTTRON applications at scales that cannot be cost effectively realized in a field or laboratory study.	Nonspecific -- Finding and fixing scalability issues	Not building-specific -- Defined applications/ simulations	Nonspecific	Still in Progress -- Goal is to develop simulation that demonstrate deployment at scale and develop metrics for scalability in a relevant deployment so that problem areas can be revised. Apps that are "good fit" for implementing with VOLTTRON include 1) ones that naturally call for a publish/subscribe type architecture; 2) ones that can make good use of functionality that is part of VOLTTRON system, and 3) are readily conceived as performing tasks that can be accomplished by autonomous, but communicating agents.	http://energy.gov/sites/prod/files/2015/08/f25/11.%20Unified%20Control_ORNL_Kuruganti%20%28Kuruganti%29.pdf
Transaction Network Platform Research for Autonomous Control HVAC Controls	2014	Prototype Field Test	Fountain City Central Baptist Family Life Center	ORNL	EERE	Focused on rooftop unit (RTU) thermostats and a centralized control that coordinates operation to achieve reductions in peak energy use. A prototype of this new control system was built and deployed in a large gymnasium to coordinate the four RTUs.	HVAC	Gym/community center	Fountain City, TN (TVA)	Based on data collected while operating this prototype, we estimate that the cost savings achieved by reducing peak power consumption is sufficient to repay the cost of the prototype within a year.	http://btric.ornl.gov/cbcfamilylifecenter20140201weeklyresults.pdf

Study Title	Year/ Time Period	Type of Study	Host	Principal Investigators	Sponsors	Focus of Study	Application (e.g., HVAC, Refrigeration, etc.)	End-User/ Building Type	Location (Utility Region)	Key Outcomes/ Notes	Links to Presentations/ Sources
Transformative wave (Twave) Catalyst/eIQ Platform (series)	2014-	Field Study	TWave	TWave, PNNL	EERE	Determine whether VOLTTRON-based apps can be used with and add value to TWave products including the Catalyst RTU retrofit product/technology.	HVAC, BAS	Small-to-medium sized commercial employing RTUs	Kent, Washington (PSE)	Determined that VOLTTRON can 1) operate on low-cost platform, 2) operate in the cloud; 3) move the intelligence from the site-level controller to the zone level controller; 4) operate both energy efficiency and demand response on the same platform. Utility incentives could help bring down the cost and help with market transformation. Savings need to be verifiable.	http://energy.gov/sites/prod/files/2015/08/f25/09.%20Volttron%20Conference%20Presentation%20%28Sipe%29%20%281%29.pdf
Twave 1 -- LA restaurant	2015-2016	Field Study	TWave	TWave, PNNL	EERE	VOLTTRON controllers and catalyst RTU retrofit: Economizer FDD, Performance Benchmarking, RTU Coordination, Demand Response, measurement and verification (M&V)	HVAC	Two quick serve restaurants	Los Angeles, CA (MVU/LADWPI)	TBD: Cloud-based VOLTTRON employed.	
Twave 10 -- Everett Library	2015-2016	Field Study	TWave	TWave, PNNL	EERE	VOLTTRON controllers and catalyst RTU retrofit: Economizer FDD, Performance Benchmarking, RTU Coordination, Demand Response, and Tenant Billing	HVAC	Library	Everett, WA (PSE)	TBD: Local version of VOLTTRON employed.	
Twave 11 -- Saratoga Gym	2015-2016	Field Study	TWave	TWave, PNNL	EERE	VOLTTRON controllers and catalyst RTU retrofit: Economizer FDD, Performance Benchmarking, RTU Coordination, Demand Response	HVAC	Gym/ community center	Saratoga, CA (PG&E)	TBD: Cloud-based VOLTTRON employed.	
Twave 12 -- Furniture Store (WA)	2015-2016	Field Study	TWave	TWave, PNNL	EERE	VOLTTRON controllers and catalyst RTU retrofit: Economizer FDD, Performance Benchmarking, RTU Coordination, Demand Response	HVAC	Two furniture stores	Everett/Lynnwood, WA (PSE, Snohomish)	TBD: Local version of VOLTTRON employed.	

Study Title	Year/ Time Period	Type of Study	Host	Principal Investigators	Sponsors	Focus of Study	Application (e.g., HVAC, Refrigeration, etc.)	End-User/ Building Type	Location (Utility Region)	Key Outcomes/ Notes	Links to Presentations/ Sources
Twave 2 -- Kent Office/Mfg.	2015-2016	Field Study	TWave	TWave, PNNL	EERE	VOLTTRON controllers and catalyst RTU retrofit: Economizer FDD, Demand Response, M&V	HVAC	Office/manufacturing	Kent, Washington (PSE)	TBD: Local version of VOLTTRON employed.	
Twave 3 -- Seattle Drug Stores	2015-2016	Field Study	TWave	TWave, PNNL	EERE	VOLTTRON controllers and catalyst RTU retrofit: Economizer FDD, Performance Benchmarking, Demand Response	HVAC	Three drug stores	Seattle, WA (PSE, Seattle City Light)	TBD: Local version of VOLTTRON employed.	
Twave 4 -- Everett Office	2015-2016	Field Study	TWave	TWave, PNNL	EERE	VOLTTRON controllers and catalyst RTU retrofit	HVAC	Office building	Everett, WA (PSE, Snohomish)	TBD: Local version of VOLTTRON employed.	
Twave 5 -- Atlanta Office	2015-2016	Field Study	TWave	TWave, PNNL	EERE	VOLTTRON controllers and catalyst RTU retrofit:	HVAC	Office building	Atlanta, GA (Georgia Power)	TBD: Local version of VOLTTRON employed.	
Twave 6 -- Everett Casino	2015-2016	Field Study	TWave	TWave, PNNL	EERE	VOLTTRON controllers and catalyst RTU retrofit: Economizer FDD, Performance Benchmarking, RTU Coordination, Demand Response, M&V	HVAC	Casino	Everett, WA (PSE, Snohomish)	TBD: Local version of VOLTTRON employed.	
Twave 7 -- Tacoma Casino	2015-2016	Field Study	TWave	TWave, PNNL	EERE	VOLTTRON controllers and catalyst RTU retrofit: Economizer FDD, Performance Benchmarking, RTU Coordination, Demand Response, M&V	HVAC	Casino	Tacoma, WA (PSE, Tacoma Power)	TBD: Local version of VOLTTRON employed.	
Twave 8 -- Seattle Office	2015-2016	Field Study	TWave	TWave, PNNL	EERE	VOLTTRON controllers and catalyst RTU retrofit: Performance Benchmarking and Tenant Billing	HVAC	Mid-rise office	Seattle, WA (PSE, Seattle City Light)	TBD: Cloud-based VOLTTRON employed.	
Twave 9 -- Cedar Rapids Office	2015-2016	Field Study	TWave	TWave, PNNL	EERE	VOLTTRON controllers and catalyst RTU retrofit: Economizer FDD, Performance Benchmarking, RTU Coordination, Demand Response, M&V, and Tenant Billing	HVAC	Large retail	Cedar Rapids, IA (Alliant)	TBD: Cloud-based VOLTTRON employed.	

Study Title	Year/ Time Period	Type of Study	Host	Principal Investigators	Sponsors	Focus of Study	Application (e.g., HVAC, Refrigeration, etc.)	End-User/ Building Type	Location (Utility Region)	Key Outcomes/ Notes	Links to Presentations/ Sources
Unified HVAC and Refrigeration Control Systems for Small Footprint Supermarkets	2015-	Lab Testing	Emerson Climate Tech. -- Emerson Labs	ORNL, Emerson	EERE	Develop control techniques for reducing peak demand and improving energy efficiency of rooftop units and supermarket refrigeration systems and integrate photovoltaic sources	HVAC, Refrigeration	Small grocery stores	Sydney, OH (not applicable)	Successful in demonstrating savings potential of developing algorithms to perform defrost on-demand and retrofit VOLTTRON platform and control app to Emerson controller to perform on-demand defrosting. Minimal retrofit cost is goal, such that low-cost, low-touch retrofit control technology can be used to facilitate transactive opportunities for energy efficiency with the electric systems.	http://energy.gov/sites/prod/files/2015/08/f25/11.%20Unified%20Control_ORNL_Kuruganti%20%28Kuruganti%29.pdf
VOLTTRON Enabling Vehicle-to-Building Integration	2014	lab Testing	PNNL Lab Homes	PNNL/Argonne	EERE/OE	Demonstrated VOLTTRON-enabled electric vehicle charging station at PNNL Lab Homes.	Electric vehicle charging	Vehicle-to-single-family home integrated charging	Richland, WA (not applicable)	Demonstrated that VOLTTRON was appropriate platform to use to build flexible and responsive controller for charging station.	http://energy.gov/sites/prod/files/2015/08/f25/15.%20VOLTTRON_VirginiaTech%20%28Pratt%29.pdf
VOLTTRON Transactive Control Node	2014	Case Study	Quality Logic	Quality Logic	PNNL Future Power Grid Initiative -- Grid PNW-SGDP	Case examined: An implementation of Transactive energy that uses exchange of incentive/feedback schedules and local information to make decisions. . . Built on VOLTTRON platform.	Control Node	Three modeled homes with electric vehicle chargers	Nonspecific	Demonstrated that VOLTTRON was "easy" platform to use to demonstrate case. Three customers defined with different rules (bargain hunter, flexible users, demanding consumer).	http://energy.gov/sites/prod/files/2015/08/f25/10.%20VolttronTCNodeCaseStudy%20%28Rankin%29.pdf
Clean Energy and Transactive Campus Project	2015	Field Study	PNNL, Washington State University, and University of Washington	PNNL, Washington State University, and University of Washington	EEER/OE/ Washington Department of Commerce	To demonstrate that transaction-based controls can lead to a clean energy transformation and a reliable and stable electric grid. Create a research and development testbed for renewable integration, efficiency, and grid services.	Increasing the hosting capacity of energy efficiency and renewable energy in commercial buildings	Institutional commercial buildings in large campus settings	City of Richland, Avista, Seattle City Light, and Puget Sound Energy	"Recipe" for replication of experiments to help utilities, municipalities, and building owners who are facing larger deployments of clean energy technologies, aging infrastructure, and new regulations. Create a state-of-art testbed that can be used to lead the nation in clean energy research and development and in creating clean energy jobs.	http://bgintegration.pnnl.gov/volttron.asp

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