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# Home Energy Management Retrofit Control Platform

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**Abstract**

Residential buildings consume significant amounts of energy for equipment, such as heating, ventilation, and air conditioning (HVAC), water heating, appliances, lighting, and general plug/outlet loads. In 2009, residential buildings accounted for 21 Quads of primary electrical energy consumption, which is 21% of the total primary energy consumption in the United States [1]. Currently, this equipment is operated based on homeowner's schedule with limited or no feedback on their impact to the state of the electric grid. However, in the future this equipment can be controlled to manage the electricity usage, which will mutually benefit the homeowner and the utility companies. As such, significant potential for savings and demand control exists through the deployment of a retrofit control system for monitoring and coordinating various residential energy loads. Appliance energy loads can be dispatchable, making them responsive to the electric grid's needs, such as higher penetration of renewable energy. The key enabler to this strategy is a low-cost, retrofit home energy management system (HEMS) platform and standard communication methods for connecting the equipment to the HEMS. The HEMS must offer energy savings through enhanced control and must demonstrate load flexibility through intelligent dispatch. Once the control of residential loads for utility benefits is established, market-based financial incentives shall be developed for building-to-grid transactions [2]. A HEMS for homes will enable: (1) improved energy efficiency and reduced peak demand, (2) connectivity across loads to make them responsive to grid needs at the distribution level, and (3) diagnosis of equipment inefficiencies. In this paper, we discuss an open-source HEMS platform for providing retrofit connectivity across multiple loads in residential buildings and supervisory control of these loads to improve energy efficiency, enable load flexibility, and reduce peak demand.

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## 1. Introduction

The overarching goal of this work is to develop, deploy, and demonstrate a home energy management system (HEMS) that increases the operational flexibility of loads in residential buildings to improve energy efficiency, improve comfort, reduce peak demand, and enable building-to-grid integration through load coordination. Residential homes have variable loads due to weather and household occupancy schedules. The major energy consuming equipment in a home includes HVAC, water heating, appliances, lighting, and plug loads. This equipment can be controlled to manage electricity usage to offset periods of peak demand on the electrical grid.

Residential buildings account for 21 Quads of primary electrical energy consumption in the United States, which is 21% of the total nationwide primary energy consumption [1]. HVAC, water heating, and appliance loads account for approximately 83% of the total energy use in residential buildings [1]. While HVAC systems

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are a significant portion (54%) of the total energy consumption, the contribution of other appliances can provide a significant impact on peak demand. In a 2012 study conducted by Pacific Northwest National Laboratory (PNNL), PNNL researchers found that the peak reduction potential for grid-enabled appliances is 19% of the system peak [3]. With proper HEMS functionality, a significant portion of appliance energy use can be operated as dispatchable loads. Operation as dispatchable loads enables responsiveness to electric grid needs and higher penetration of renewable energy, energy storage, and electric vehicle technologies. Despite the variety of residential building types, the energy use profiles are similar.

During the past decade, there has been increased penetration of renewable energy alternatives, such as wind and solar, with projections of continued growth. In addition, energy conservation has been promoted through utility and government incentives. However, most homeowners still do not have a clear understanding regarding their energy consumption. Thus, there is an opportunity for a system to autonomously manage energy consumption in a home. It has been shown that HEMS can help both homeowner and utilities save energy and cut costs, and novel retrofit-compatible connectivity and automation systems are required for unlocking the full benefits and transactive potential of these systems in residential buildings.

Numerous issues impede wide-scale adoption and deployment of HEMSs in residential buildings. These issues can be described as: hardware and software issues; unclear or conflicting performance objectives; undefined value for owners, operators, and service providers; and a lack of clear understanding of products and services needed to support the HEMS market. The hardware and software issues include: (1) multiple interoperable communication protocols developed by individual organizations which are often proprietary, (2) vulnerabilities leading to security threats to personally identifiable data, (3) complexities in retrofit integration reducing functionality, (4) high cost of deployment, and (5) reliability problems of products on the market [4]. The communication issues are due to a variety of industry offerings for communications and functionality without common standards. Standard communications for building equipment enables the concept of a connected home or connected building, which also enables common user interfaces and HEMS capabilities.

HEMS also offer value in the form of user interfaces, improved comfort, reduced energy bills, and visibility and detection of faults—all of which are achievable and can encourage consumer adoption. The utility companies themselves can develop market-based approaches to encourage residential load participation for dispatch in order to reduce service interruptions and improve the speed at which they are able to recover from outages. Manufacturers, suppliers, and service providers struggle with anticipating markets for new products because of the unclear value proposition and the uncertainty of who will bear the costs. Finally, consumers struggle with the cyber- and physical-security implications of a connected infrastructure and want to keep their lives private.

In a home, the HEMS needs to be able to communicate with different devices, monitor and control them, receive signals from the utility, provide feedback to the users, secure the gathered information, and create a schedule based on utility request and homeowner's criteria (Figure 1, left). In a community, each HEMS should be able to access some information regarding different homes' energy usage and coordinate the house energy consumption based on other home's needs and utility's request to perform load shifting, and reduce peak demand (Figure 1, right).

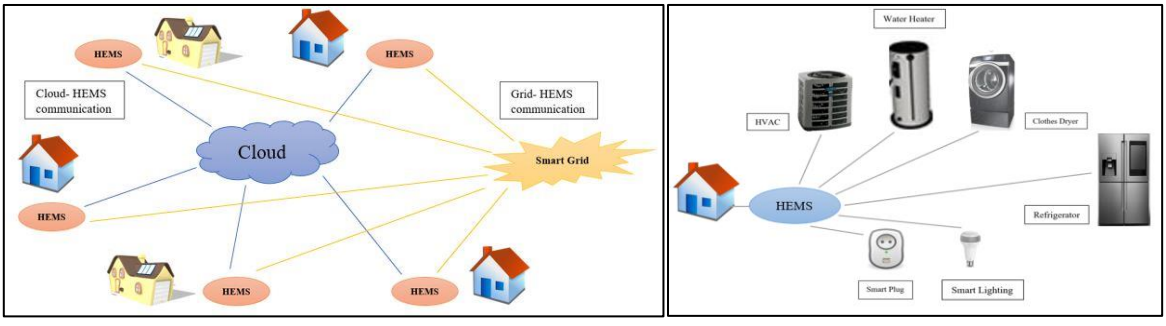



Figure 1. Left picture shows the coordination between HEMS in a community and the smart grid.
Right picture shows the functionalities of HEMS in a home

Residential control system research and various open-source and proprietary energy management systems have resulted in an influx of new products to market [5], [6], [7], [8]. Most of these energy management systems can monitor and control the devices with the limitations of supporting a limited number of devices manufactured

by specific vendors. Also, most of these systems lack support for load coordination such as demand response (DR), load shifting, or reducing peak demand. Many of these systems do not provide any feedback to the homeowners or offer algorithms or intelligence to save energy or perform load coordination. Most systems also lack standard cybersecurity features like authentication.

The open-source energy management system proposed here will address many of these concerns. The platform is built on top of the VOLTTRON open-source transactional control platform which can facilitate the integration of different devices with different communication technologies [9]. The VOLTTRON platform can communicate with the utility to receive DR signals. The platform facilitates the development of intelligent applications that can utilize utility information to save energy and reduce costs for the homeowners and the utility. VOLTTRON also provides access to cybersecurity tools for securing applications and devices.

The overall objective is to develop, demonstrate, and deploy interoperable solutions that can bridge communication technologies, address the main issues affecting a connected environment, and accelerate the adoption rate of products to enable intelligent control of devices inside a connected home. One of the main components of this strategy will need to be the development of a cooperative HEMS control system based on the open-source VOLTTRON platform, which addresses the impediments to adoption and enables the full potential of the connected equipment, including improved energy efficiency, reduced energy costs, reduced peak demand, and improved comfort.

A desired outcome of this project is to demonstrate retrofit connectivity across multiple loads in residential hubs. This technology will facilitate seamless integration of rooftop renewables, small-scale energy storage, and electric vehicle adoption.

A monitoring and supervisory control system for homes can enable (1) improved energy efficiency and reduced peak demand, (2) connectivity across various loads in a home to make them collectively responsive to grid needs at the distribution level, (3) diagnosis of equipment inefficiencies, and (4) simple interoperability across protocols, manufacturers, and industry sectors. However, these systems must be retrofit-compatible for unlocking the energy savings and transactive potential of the residential buildings.

## 2. HEMS Control System Architecture and Design

The main goal of a HEMS is to improve the energy consumption in homes and buildings. It also aims to help the utilities by enabling control of energy usage to reduce peak demand and support load shifting. To satisfy these requirements, each HEMS needs to support certain functionalities such as monitoring and controlling devices, supporting demand response (DR), authentication, and security.

In this section, the system architecture of the proposed open-source HEMS is described. Commercial offerings are usually proprietary systems with fixed functionality and sparse communication options. The proposed architecture, on the other hand, is intended to provide open-source hardware, communications, and software with a variety of communication options. The communication options should include IEEE 802.3 (Ethernet), IEEE 802.11 (Wi-Fi), and Bluetooth and appliance communications such as HomePlug, CEA-2045, and Z-Wave. As shown in Figure 2 the architecture consists of four main layers.

1. **User Interface:** A web-based user interface and a phone/tablet application will be provided for easy interaction between the user and the software.
2. **Applications and Intelligence:** The implementation of many applications that the software should provide lies in this layer, including applications for DR, scheduling, and notifications/alerts. This layer will also include the implementation of smart algorithms such as load shifting, price management, and energy usage pattern analysis. Applications can access a database for data archival and retrieval.
3. **Framework services:** This layer will provide VOLTTRON platform-centric services, including software drivers to access multiple devices, access to communication message bus (publish/subscribe), and networking services. This platform is explained in more detail in Section 2.1.
4. **Communication Technologies and Protocols:** This part will include various communication technologies and protocols that will be supported by the software. In an energy management system, the system should be able to provide seamless communication between different smart devices and sensors that are running different communication technologies [10]. For wired communication, IEEE802.3 and HomePlug Green PHY [11] are the leading communication standards. ZigBee [12], Z-Wave [13] , and low-power Wi-Fi are the leading technologies for wireless communication [14]. In order to design a

robust and flexible networking infrastructure, the characteristics and requirements of each of these technologies need to be understood [14].

### *2.1. VOLTTRON*

VOLTTRON is a distributed agent platform developed by PNNL [9], [2]. Its architecture is based on the Multi- agent System (MAS), and it will be used as a platform for implementing agents. MAS is a community of intelligent agents which can work together and coordinate their decisions to achieve the system goal. This platform enables the deployment of intelligent MAS that can be used to optimize the residential energy consumption and at the same time satisfy the user's comfort conditions [15].

The VOLTTRON platform's architecture consists of authentication and authorization (AA), agent instantiation and packaging (AIP), communication services (CS), directory services (DS), and information exchange bus (IEB) modules. The platform can run on small computers and requires a small amount of memory. Various devices with different communication technologies and protocols can be integrated into VOLTTRON and be monitored and controlled.

Researchers at Oak Ridge National Laboratory (ORNL) have evaluated different retrofit-compatible, single-board computing platforms equipped with VOLTTRON for potential use in the control of commercial and residential building loads. After the setup and installation of VOLTTRON on three separate computing platforms, their behavior and performance were tested. ORNL researchers conducted a controlled experiment to ensure thorough testing of the configuration and to derive preliminary benchmarks of performance while pushing the hardware to a specified threshold.

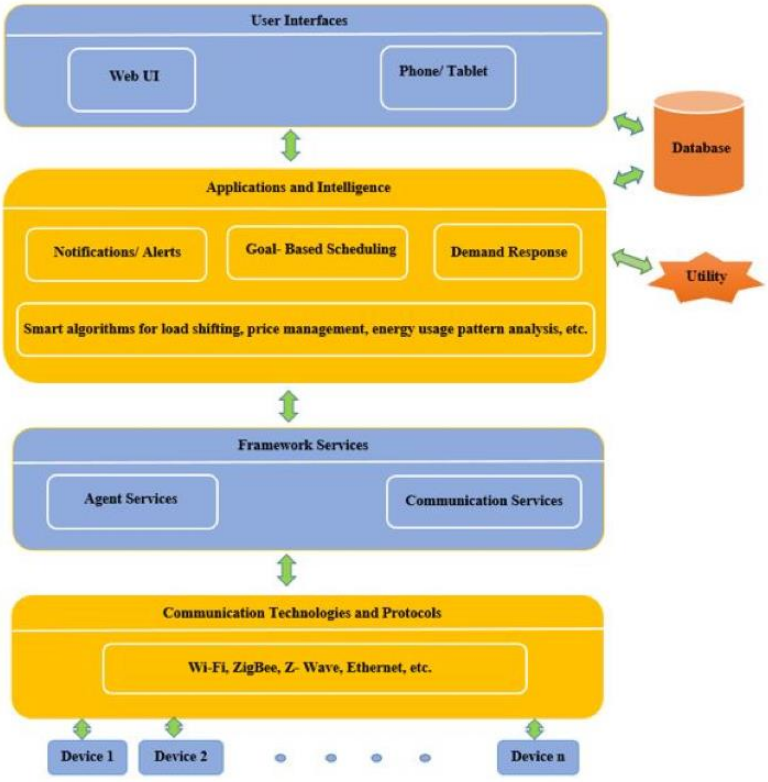



Figure 2. HEMS software architecture.

A simple Modbus read operation from the five thermostats used in the experiment (as illustrated in the setup in Figure 3) was tested in four execution scenarios:

1. without VOLTTRON, using simple repeated reads from the thermostats;

2. as an agent using the VOLTTRON platform;
3. as an agent using the VOLTTRON platform and publishing values on the VOLTTRON message bus while a SMAP agent pushed the data to a remote SMAP server; and
4. as an agent using the VOLTTRON platform and publishing values on the VOLTTRON message bus while a MySQL agent pushed the data to a local MySQL database.

The scan rate and the associated timeout for communicating with the Modbus thermostat devices were varied from 0.01 seconds to 0.5 seconds (from 100 scans per second to 2 scans per second). Each scan consisted of a Modbus read of a thermostat device to obtain the temperature measurement value. In other words, 100 scans per second is equivalent to reading from one thermostat 100 times per second or from ten thermostats 10 times each per second. In the test execution, the communication was sequenced between all five thermostats evenly to achieve a realistic test of communicating with multiple devices. For each test condition of the scan rate, each thermostat was read 50 times to obtain a reasonably statistical sample to be used for benchmarking. The data from the benchmarking is summarized in Figure 4.



Figure 3. VOLTTRON hardware testing with Modbus thermostats.

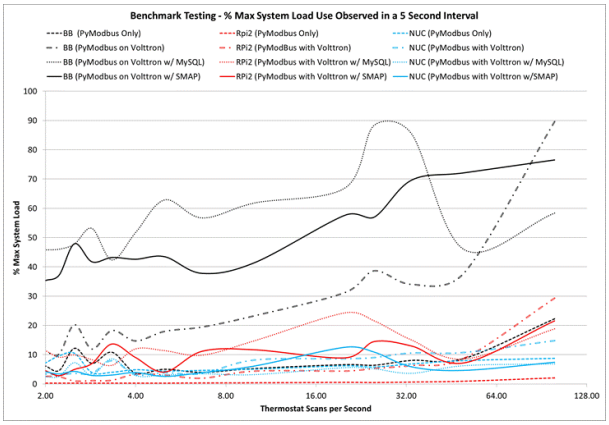



Figure 4. VOLTTRON hardware results – plot of percent maximum system processor usage over five second interval for all three SBC devices.

## *2.2. Device Agent*

An energy management system should be capable of: 1) communicating with devices; 2) providing monitoring; and 3) achieving control. The device agent (DA), shown in Figure 5, should enable these capabilities. There is a DA associated with each device, such as an HVAC system, appliance, or water heater, to be controlled. A configuration file is provided to the DA to initialize the communication with the device. The DA accesses the device data by subscribing to proper topics. It can also change the device data by publishing to desired topics. The DA is capable of executing the steps in a plan provided to it by taking appropriate control actions.

To initialize a DA, the configuration file associated with each device needs to be passed to the DA class. This file may include the name of the device, the IP address, the port number, the communication protocol, etc. Based

on the parameters in the configuration file, an instance of the device will be created and the related parameters are set.

After the initialization is done, the DA can subscribe to the messages sent by the device, obtain parameter values, or set them. The topic of the messages depends on the device and the protocol being used. For the case of a thermostat, the topics may be the current temperature, the target temperature, system status, etc. Also, whenever a plan is designed, based on a demand response signal, system goal, or user criteria, the DA should be able to execute the steps in the proposed plan. For a thermostat, the schedule may contain temperature set points at different times of the day.

```
Class DeviceAgent
{
        //Initialize a DeviceAgent object,
        //set parameters based on config file, and connect to the device
        DeviceAgent (string configFilePath)
        {
                //Reads the config file and set parameters
                SetParameters(configFilePath);
                //Connect to the device using its address (Example: IP: Port)
                Connect (deviceAgent Address);
        }

        //Subscribe to the updates regarding the topic
        Subscribe (string topic)
        {
                //Subscribe to the topic
                // (Example: testtopic/Livingroom/Temperature)
                client. Subscribe(topic);
        }

        //Ask for the latest value of the subscribed topic
        string GetValue (string topic)
        {
                return topicValues.topic.value;
        }

        //Change the value of the topic
        bool SetValue (string topic, string value)
        {
                client. Publish (topic, value);
                if (GetValue(topic) == value)        return true;
                return false;
        }

        //Execute the steps in the plan
        void ExecutePlan (string [] plan)
        {
                Foreach step in plan
                        Execute(step);
        }
}
```

Figure 5. Device Agent

### *2.3. Demand Response Agent*

To support demand response (DR) and reduce peak demand, a lot of coordination between the utilities and the users is needed. Applications on the customer side should be able to receive signals from the smart grid. Algorithms need to be developed to reduce peak demand, to support load shifting, and to coordinate between energy usage and consumption.

A demand response agent (DRA), shown in Figure 6, should be capable of receiving DR signals for reducing peak demand. Whenever a DRA receives a signal from the utility, it sends that signal to an intelligence agent (IA), shown in Figure 7, and asks for the appropriate actions based on the received signal. As soon as the IA receives the signal from the utility, it runs smart algorithms and define the tasks required, based on the received signal and system goal. The DA is then notified to take appropriate action based on the plan.

```
Class DRAgent
{
        //Initialize a DRAgent object,
        //set parameters based on config file, and connect to the agent
        DRAgent (string configFilePath)
        {
                //Reads the config file and set parameters
                SetParameters(configFilePath);
                //Connect to the agent using its address
                Connect (drAgentAddress);
        }

        //Waits for a demand response signal
        Void WaitForDRSignal ()
        {
                while(true)
                {
                        if (drSignalReceived)
                        {
                                //Notify the intelligence agent when a new drSignal is received
                                IntelligenceAgent. DefineTasks (drSignal, drEnabled);
                        }
                }
        }
}
```

Figure 6. Demand Response Agent.

### *2.4. Intelligence Agent*

The IA is responsible for all of the scheduling. It creates a schedule based on the homeowner and system goals and preferences. The plan is passed to appropriate DAs. Whenever a DR signal is received, the IA is notified and modifies the plan based on the received signals. It also makes recommendations and provides feedback based on homeowner energy usage behavior.

The IA aids users by creating a plan based on the system goal and demand response signal received from the utility. For example, during peak demand, the IA can postpone non-critical tasks such as laundry or dishwashing and start certain devices, such as HVAC system and water heater, based on the information it has regarding the homeowner's schedule. From the created schedule, the IA can notify the appropriate devices and change their settings. It can also make recommendations and provide feedback by performing data analysis on the energy consumption history and the system goal. Since most homeowners do not have a good understanding of their energy usage, a HEMS with intelligence will aid in making better decisions for optimal control to achieve reduced energy consumption.

```
Class IntelligenceAgent
{
        //Initialize an IntelligenceAgent object,
        //set parameters based on config file
        IntelligenceAgent (string configFilePath)
        {
                //Reads the config file and set parameters
                SetParameters(configFilePath);
        }

        //Create a plan based on the demand response signal
        // and notify related device agents
        void DefineTasks (string DRSignal, bool drEnabled)
        {
                if (drEnabled)
                {
                        Dictionary<string, string []> plan = CreatePlan(drSignal);
                        string [] relatedDeviceAgents = plan. Keys;

                        foreach deviceAgent in relatedDeviceAgents
                                deviceAgent. ExecutePlan(plan[deviceAgent]);
                }
        }

        // Provides feedback to the users using the energy usage history
        //and priority list
        string [] ProvideFeedBack (string [] priorityList, string dataLogPath)
        {
                //provide feedback based on energy consumption
                string [] usageFeedback = AnalyzeEnergyConsumption(dataLogPath);

                // find system goal based on priority list
                string systemGoal = FindSystemObjective(priorityList);
                // Analyze data and try to optimize data usage using system goal
                string [] suggestions = MakeSuggestion (dataLogPath, systemGoal);

                return usageFeedback + suggestions;
        }
}
```

Figure 7. Intelligence Agent

## 3. Challenges and Future work

As described above, the proposed open-source HEMS supports monitoring and controlling devices both manually and automatically. The system can communicate with the smart grid and support DR while providing secure communication between devices and the system. It also helps utility companies by providing smart algorithms that can reduce peak demand.

To better support DR, more information regarding each home's energy consumption in a community is needed. Since the smart grid can provide this information at varying time granularity, the system should be able to manage and analyze the tremendous amount of data provided to it. This also introduces the scalability challenge of connected homes. There may be modifications needed to the energy management system to efficiently and robustly handle the energy usage for thousands of homes that might constitute a community.

New smart algorithms should be developed in order leverage and analyze this data. Having a complete understanding of the data will ensure that both the public and the utility are making informed decisions for coordinating the energy usage and consumption, reducing peak demand, and supporting load shifting.

Fault detection is another feature that should be supported by the system to save energy. In some cases, sensors can be added to existing devices and appliances for diagnostic purposes. In any case, analyzing the behavior of the device over a period of time can help determine whether the system is working properly or not.

## 4. Conclusion

Using HEMSs is a growing sector in the era of smart grids and smart homes. A significant amount of energy is consumed by dwellings, and this shows the importance of improving the energy consumption in residential buildings. The primary goal of a HEMS is to save energy by providing information to the users regarding energy consumption and help them adapt their energy usage behavior based on the feedback they receive from the system.

Different energy management systems have been introduced which support monitoring and controlling certain devices. However, existing systems can only support devices with certain types of communication protocols. They do not use information regarding user's energy consumption to save energy or support DR or security.

In this paper, we proposed an open-source HEMS that supports DR, provides secure and protected communication between devices and the system, and supports monitoring and controlling a wide number of devices. The proposed HEMS can also help the utility and the homeowners by providing smart algorithms that can create schedules based on system goals and reduce peak demand.

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