

Battery Management and Application for Energy-Efficient Buildings

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ABSTRACT

As the building stock consumes 40% of the U.S. primary energy consumption, it is critically important to improve building energy efficiency. This involves reducing the total energy consumption of buildings, reducing the peak energy demand, and leveraging renewable energy sources, etc. To achieve such goals, hybrid energy supply has become popular, where multiple energy sources such as grid electricity, on-site fuel cell generators, solar, wind, and battery storage are scheduled together to improve energy efficiency.

In this work, we focus on the application and management of battery storage for energy-efficient buildings. We will first introduce a system-level approach to co-schedule the usage of battery storage (in addition to grid electricity) with the control of building HVAC (heating, ventilation, and air conditioning) system, to reduce the total building energy cost, including the electricity consumption charge, the peak demand charge, and the battery cost. Then, in a separate formulation, we will introduce another system-level study to reduce the energy cost of EV charging and other fixed building energy load through the usage of battery storage and solar PV. Finally, we will present an ARM processor based programmable embedded battery management system (BMS), which monitors battery status, controls charging and discharging at the circuit level, and provides battery protection. The system also works with off-the-shelf battery management IC (Texas Instrument BMS sensor IC) from industry. Comparing to conventional BMS, this software module based BMS is a more suitable solution for energy-efficient buildings due to its high flexibility, scalability, and reusability.

We will introduce an industrial building testbed with battery storage and solar PV at the University of California, Riverside, and present initial field tests and simulation results for above approaches.

1. INTRODUCTION

The commercial and residential building stock consumes 40% of the U.S. primary energy consumption, 40% of the greenhouse gas emissions, and 70% of the electricity use [6]. Improving building energy efficiency is therefore critically

important to address the nation's energy and environmental concerns. To achieve this goal, hybrid energy supply is being adopted, where multiple energy sources are scheduled together to improve the energy efficiency by reducing the peak demand and leveraging renewable energy sources such as solar and wind. In this work, we focus on the usage of battery storage, in addition to grid electricity, to improve the building energy efficiency. We will address the problem from both the system level, by proposing approaches to utilize batteries for reducing the total energy cost, and from the circuit level, by developing an advanced battery management system (BMS) to monitor, control and protect the batteries.

At the system level, energy-efficient smart buildings today employ sophisticated and distributed building management systems. As the brain of modern buildings, the building management system controls many aspects of the building operations including heating, ventilation and air conditioning (HVAC), lighting, fire and security, electric vehicle (EV) charging, etc. In particular, HVAC system accounts for 50% of the building energy consumption, and the control of it is critical for building energy efficiency. The demand side scheduling of HVAC control depends on the availability of battery storage and the price of grid electricity, and the supply side scheduling of battery storage requires the knowledge of the HVAC demand. Therefore, we believe it is essential to *address these two aspects in an integrated framework to achieve the maximal energy efficiency*. In particular, it is important to address the management and application of battery storage together with HVAC scheduling. In the literature, various HVAC control mechanisms [14, 23, 22, 7, 21, 20, 13, 24] are proposed for reducing energy consumption and cost. There are also approaches proposed for efficiently scheduling multiple energy sources [9, 15, 16, 19, 11]. However, there has been little work on formulating the interactions between the two aspects and addressing them together. Furthermore, most of the HVAC control work in the literature are either based on simulation results without validations through field tests, or more focused on feasibility demonstration in the field and not the optimal design of the control algorithm. In this work, we propose a novel system-level algorithm for the building management system to *co-schedule the HVAC control with the usage of battery storage system* and grid electricity to reduce the building energy cost, including both the electricity consumption charge and the peak demand charge, as introduced in Section 2. The algorithm is based on model predictive control (MPC) and leverages the battery model from the battery management system in Section 4.

We also conduct studies on utilizing battery storage, together with solar PV and grid electricity, to reduce the en-

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ergy cost for EV charging and other fix building energy load (i.e., assuming all energy loads are given and no co-scheduling is conducted). As an emerging building application, EV charging is becoming a major load on the demand side (especially in residential buildings).

At the circuit level, we develop a software module based BMS that monitors the battery status, controls charging and discharging of the battery, and provides battery protection. The BMS computes and indicates state of charge (SOC), remaining capacity, and state of health (SOH). These measurements will be used at the system level to control the scheduling of the battery storage.

We use the building testbed at the Center for Environmental Research and Technology (CE-CERT) in University of California, Riverside (UCR) to identify energy saving opportunities, provide proper simulation parameters, and ultimately implement and evaluate our approaches through field tests. The building testbed is an administrative building (1084 Columbia Ave) at the UCR CE-CERT center, which is located off campus in an industrial zone. It pays standard industrial electrical time of use rates which includes peak and off demand charges. The building HVAC system consists of 16 packaged rooftop units, each with its own control interface. Over the last 18 months, we have installed additional measuring and control instruments for the HVAC system. To implement our MPC-based control algorithm that controls and coordinates the 16 rooftop units, a programmable controller is deployed, which can continuously monitor the real-time energy demand, and send control commands to the 16 units. The building testbed is also integrated with the following infrastructure and facilities available in the UCR CE-CERT center: 1) 0.5MW solar PV on car ports connected through three separate inverters to three CE-CERT buildings, including the building testbed, 2) 0.54 MWh Lithium-ion battery storage connected with three buildings including the testbed, 3) 0.54 MWh Lithium-ion mobile battery storage, 4) multiple L2 charger and one L3 charger for EV charging.

Next, we introduce our approach for co-scheduling HVAC control and battery usage for energy cost reduction in Section 2. We present our study on using battery storage to reduce energy cost for EV charging and fixed building loads in Section 3. We present our BMS design in Section 4. Finally, Section 5 concludes the paper.

2. CO-SCHEDULING OF HVAC CONTROL AND BATTERY USAGE

To reduce building electricity energy cost, there are two main portions of the electric bill that we are able to control – the total amount of the electricity used, measured in kWh, and the peak demand of electricity, measured in kW. As an example, for our testbed building, in the month of June 2013, the peak demand charge was \$758.75, with a peak demand at 72.4 kW and billed at \$10.48 per kW. The HVAC usage peaks around 65kW (the remaining 7.4kW of usage comes from other loads such as lighting and computers). The electricity consumption charge is \$2,390.82. Based on these numbers, a 20% peak HVAC demand reduction will amount to more than 4% reduction in total electricity energy cost. We also reviewed the electric bills for another two larger buildings in CE-CERT. Those buildings use high demand rate schedule, and the peak HVAC demand charge has an

even higher percentage in the total electricity cost (25% - 30%). It is clear that shaving the peak demand alone can bring significant reduction in building energy cost.

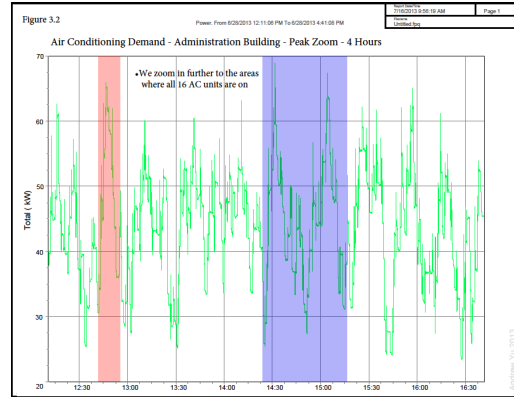


Figure 1: HVAC demand variations during peak hours (collected on the building testbed).

To investigate the peak shaving potential from the HVAC system, we conducted initial data collection and testing on our building testbed. Fig. 1 shows the peak hour (12pm to 5pm) HVAC demand of our testbed building we collected on June 28, 2013. It is clear that even within the peak hours, there are significant variations on the HVAC demand – the peak demand reaches almost 70kW when most of the AC units are turned on, while the low demand is below 30kW when only a few of the them are on. By moving ahead or delaying some of the AC units demand, we should be able to shave the peak significantly while still maintaining the temperature within the comfort zone for building occupants.

In below, we propose a MPC-based algorithm to minimize the total electricity cost, including the electricity consumption charge, the peak demand charge, and the battery overuse cost. First, Table 1, 2 and 3 summarize the notations of various parameters and variables.

Variables	Definition
b_1, b_2, b_3, b_4, b_5	battery model coefficients [10]
p_b	unit cost of battery
$SOC(t)$	state of charge
C_b	capacity of battery
R_b	internal resistance
E_b	battery lower threshold
p_{bo}	battery overuse cost
$B(t)$	battery residual electricity
C_i	battery charging current

Table 1: Notations of battery parameters

Variables	Definition
c_1, c_2, c_3, c_4	energy coefficients [12]
AC_p	AC power
$U_{upBound}$	air flow upper bound
$U_{lowBound}$	air flow lower bound
U_N	nominal voltage of AC

Table 2: Notations of HVAC parameters

Variables	Definition
$p_g(t)$	electricity price
p_p	peak power charge
$T_{upBound}(t)$	comfort zone upper bound
$T_{lowBound}(t)$	comfort zone lower bound
$Tctrl$	room states
$u(t)$	air flow
$e_g(t)$	electricity from power grid
$e_b(t)$	electricity from battery
$charge(t)$	power grid charges battery

Table 3: Notations of variables and constrains

The MPC formulation is as follows. Equations (2), (3) and (4) encode the temperature updates and constrains. Equations (5) and (6) compute the energy consumption based on airflow and set up energy constraints. Equation (7) is a constrain on HVAC air flow. Equation (8) is the open circuit voltage of battery, and (9) is the residual electricity in battery. Equations (10) and (11) are battery energy constraints. Equations (12) and (13) are battery charging constrains.

$$\min \sum_{t=j}^{j+w-1} [p_g(t)e_g(t) + p_b e_b(t) + [E_b + e_b(t) - B(t)]^+ p_{bo}] \quad (1)$$

$$Tctrl(t+1) = A_n \cdot Tctrl(t) + B_n \cdot u(t) + E_n \cdot distMPC(t) \quad (2)$$

$$T_{lowBound}(t+1) \leq C_n Tctrl(t+1) \quad (3)$$

$$C_n Tctrl(t+1) \leq T_{upBound}(t+1) \quad (4)$$

$$e = (c_1 \cdot u(t)^3 + c_2 \cdot u(t)^2 + c_3 \cdot u(t) + c_4) AC_p / 100 \quad (5)$$

$$e_g(t) + e_b(t) \geq e, e_g(t) \geq 0, e_b(t) \geq 0 \quad (6)$$

$$U_{lowBound} \leq u(t) \leq U_{upBound} \quad (7)$$

$$V_{OC}(t) = b_1 e^{b_2 SOC(t)} + b_3 SOC(t)^3 \quad (8)$$

$$+ b_4 SOC(t)^2 + b_5 SOC(t) + b_6$$

$$B(t) = SOC(t) C_b U_N \quad (9)$$

$$e_b(t) \leq B(t) \quad (10)$$

$$e_b(t) \leq U_N V_{oc}(t) / R_b / 1000 \quad (11)$$

$$0 \leq charge(t) \leq U_N C_i / 1000 \quad (12)$$

$$charge(t) \leq B(t) - E_b \quad (13)$$

$$SOC(t+1) = SOC(t) - e_b(t) / U_N / C_b \quad (14)$$

We conduct a set of simulations to evaluate the effectiveness of above algorithm for co-scheduling HVAC control with battery usage. The simulation parameters are chosen based on the building testbed. We simulate 24 hours of operation and set the predicting window of the MPC to 8 hours.

First, Fig. 2 shows the electricity consumption during each hour provided by the power grid when grid is the only available energy resource. To keep temperature within the comfort zone, the electricity consumption from 9:00 to 15:00 is very high. According to the time-of-use electricity price offered by utility companies, this period of time is also during peak hours. Such consumption profile results in high

electricity consumption charge and also high peak demand charge.

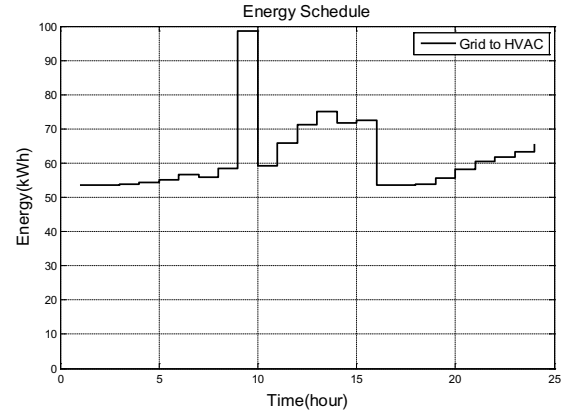


Figure 2: Energy scheduling by using grid only

When battery storage is available, we can use the above MPC-based co-scheduling algorithm to store electricity in battery during off-peak hours, and deliver electricity to the HVAC system during on-peak hours to reduce the energy cost. Fig. 3 shows the result with a 500-Ah battery storage. In the figure, the black curve represents the electricity provided by the power grid to support HVAC system. The area between black and red curves is the electricity stored in battery during off-peak hours. The area between black and blue curves is the electricity delivered by battery to reduce the on-peak electricity consumption from the grid. The higher values along red and black curves are the electricity consumption from the power grid. Compared with Fig. 2, the grid electricity consumption is much more even over time with the usage of battery storage, thus reducing both electricity consumption charge and peak demand change.

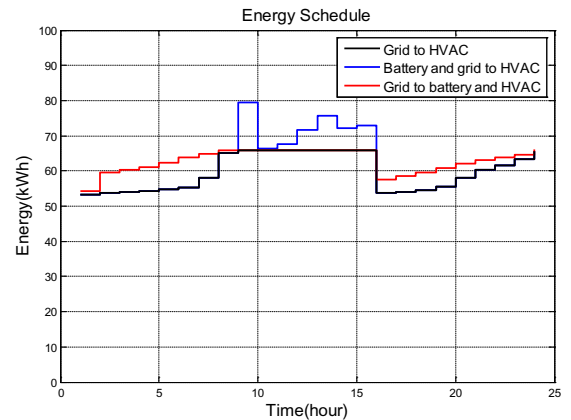


Figure 3: Energy scheduling by using power grid and battery storage

We also studied the impact of battery storage capacity on the potential energy cost saving. Fig. 4 shows the projected total energy cost reduction over a month with different battery capacities (varying from 50 Ah to 500 Ah). It is calculated by comparing the total cost by using battery

and grid electricity versus the total cost by using only the grid electricity. Note that after the battery capacity exceed 500 Ah, the total cost reduction stops increasing. That is because the battery capacity is already large enough for the current HVAC system and the addition capacity is not being utilized.

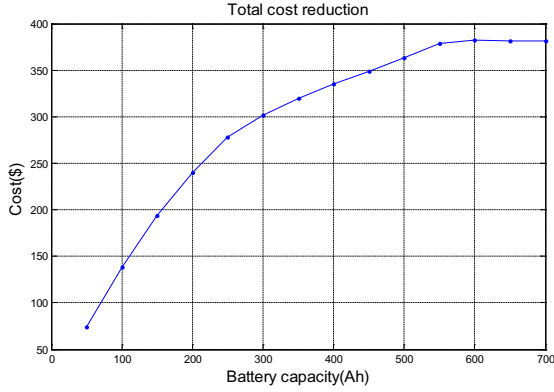


Figure 4: Total cost reduction with different battery capacities

3. BATTERY FOR EV CHARGING

We also conduct an initial study on the impact of using batter storage, together with solar PV, to reduce the energy cost for EV charging and other fixed building energy loads, as shown in this section.

Full electric vehicles (FEV) and hybrid electric vehicles (HEV) supporting plug-in charging from the grid are increasingly drawing attention from car manufacturers and customers in various aspects. HEV as well as FEV are known to have very low carbon emission and low cost per mile. PV installation in a building offers a number of benefits such as electricity bill reduction and carbon emission reduction. However, mismatch between the PV power generation and EV charging/residential load demand hinders its true benefits. An energy storage system (ESS) for a PV installation helps relieve the mismatch by storing the electrical energy during daytime and using it during the nighttime. Fig. 5 illustrates a generalized system architecture for grid-connected PV systems for EV charging. The load is powered by the PV array, power grid, or both.

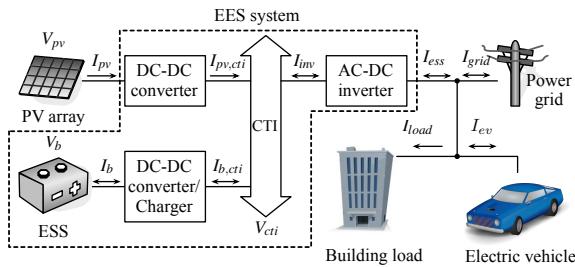


Figure 5: Electrical vehicle charging from grid-connected PV powered building.

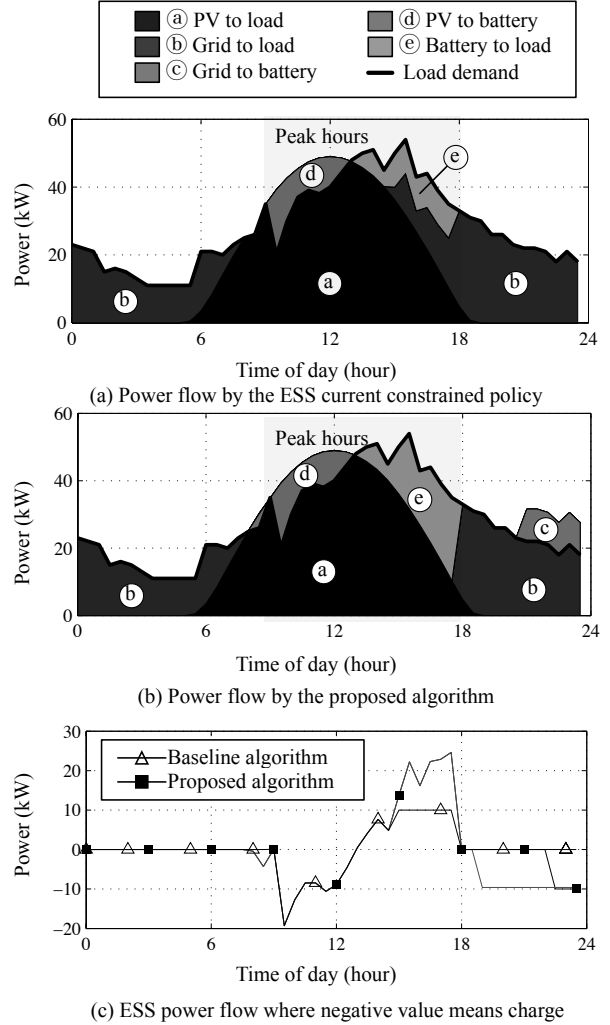


Figure 6: Power input and output variation with time for charging of Prius sized battery.

The low cost per mile of an EV largely depends on low-cost grid electricity aided by subsidies from the government. However, the financial inducement is likely to end when the EV market reaches the maturation phase, where the impact of the EV charging power on the grid would be significant [18]. EV charging power is significantly higher than the average residential load demand, which would form a large portion in the total electricity bill. Therefore, energy management considering the EV charging power and electricity bill minimization would be essential in the future.

Minimize electricity bill for a day, that is,

$$cost_{day} = \sum_{n=1}^N C[n] p_{Grid}[n], \quad (15)$$

where $C[n]$ is the unit price of the Grid electricity (\$/kWh), $p_{Grid}[n]$ is the power drawn from the Grid (W) at time slot n , and N is the number of time slots per day (note that in this study, we did not consider the peak demand charge).

We perform a simulation for the setup shown in Fig. 5 for a day. The power demand characteristic of the building is comparable to that of the UCR CE-CERT building testbed, which exhibits peak load around 60 kWh. We utilize 1 MWh LiFePO₄ batteries to use cheap electricity during the night and residual PV energy. PV panel outputs about 50 kW under 1000 W/m², which is comparable to the peak load value during the day. The power flow for two different ESS management policies, (a) maximum current constrained, and (b) proposed method are shown respectively in Fig. 6. The basic operation of the policies is to store cheap grid electricity during the night and PV power to the ESS and to use it during the peak hours where the grid electricity is expensive and to support high power requirement of EV charging. The first policy constrains the ESS current to be lower than a threshold that it might not fully utilize the benefits. The proposed policy based on [17] considers efficiency loss in the converters and rate capacity loss in the ESS to find a better solution. The resultant electricity bill for a day is 39.55 \$/day, and 34.71 \$/day, respectively.

4. BATTERY MANAGEMENT SYSTEM

In this section, we present our design of a battery management system. The basic functionalities of a BMS can be classified as monitoring the status, controlling charge and discharge, and maintaining safety operation. As a pilot study, we focus on monitoring features for BMS. A BMS monitors the status of the batteries by utilizing with electrical and thermal measurements, such as voltage, current, and temperature of the battery. With the measurements, a BMS can compute and indicate state of charge (SOC), remaining capacity, and state of health (SOH) [8].

There are many definitions and algorithms to calculate SOC, which depends on battery type and a number of cells. The typical definition of SOC, however, is based on finding scaling factor by using the maximum discharge capacity at the low rate of discharge, which can be expressed in Equation (16). Here Q_{max} is the integrated charge when the current voltage is reached to its termination from full charge. Q_{passed} is the current integrated charge [8].

$$SOC(\%) = (Q_{max} - Q_{passed}) \times 100 / Q_{max} \quad (16)$$

Many methods have been developed to achieve remaining capacity of battery for SOC estimation. One of the methods is to use voltage correlation of battery, which is very straightforward and the most traditional method. It uses a correlation between voltage and SOC of battery. Many applications are using this method due to its simplicity although it has some accuracy issue. Another method is based on battery impedance due to the fact that battery voltage drop can be corrected by the impedance dependency on the state of charge and temperature. To calculate more accurate voltage drop, Coulomb counting method is invented. Recently, an advanced gauging method, Impedance Track, has been developed. This method uses a combination of both voltage-based and current-based methods. In addition, a thermal modeling is applied to this method to compensate for temperature effects, which is one of the battery characteristics [8].

State of health information indicates time to replace with new battery to users. Knowing current capacity is not the only important information in BMS. The current health of

battery is also a critical indication. Generally, SOC calculation is based on the capacity of battery, so unhealthy battery has less maximum capacity. Without SOH, we could not achieve accurate SOC information. A typical SOH method is to find the ratio of aged capacity (Q_{aged}) and new capacity (Q_{new}). Due to variable temperature and discharge rate of battery, this method is not very accurate. Normally, SOH = 70% or 500 cycles are considered, because less than 70% causes fast IR drop in the battery characteristics [8].

$$SOH(\%) = Q_{aged} / Q_{new} \times 100 \quad (17)$$

4.1 Remote programmable networked BMS

Our system is a remote programmable networked BMS to continuously monitor the various status of battery or battery pack and execute the essential desirable computations, such as SOC and SOH. Those continuous measurements are logged in the BMS system and transmitted to a central server. Finally, the user or administrator can see the status and make appropriate feedback to battery. As pilot study, we use commercial off-the-shelf (COTS) IC for the measurement and computation for BMS. Our algorithm will be applied to the computational block in the future step. Fig. 7 shows our whole system diagram. Fig. 8 show our implementation for the programmable networked BMS. More details will be described below.

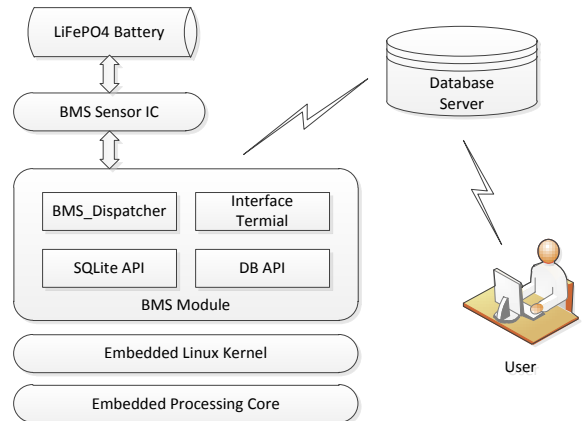


Figure 7: Battery management system (BMS) diagram

For a processing core of BMS implementation, we chose a low-cost and small form factor ARM V6 core platform, Broadcom BCM2835 system on a chip (SoC), which delivers an optimal balance of low risk, low cost, and low power for cost-sensitive applications. It provides 700MHz clock, 512Mbyte DDR2 memory, and Ethernet PHY [3].

The lithium iron phosphate (LiFePO₄) battery is used for this prototype. The basic measurements of LiFePO₄ battery is conducted by a COTS battery sensor IC (BQ34Z100 from Texas Instrument), which provides voltage, current, and temperature information to monitor and diagnosis a battery [1].

The open source Debian based embedded Linux Kernel 3.1 with I2C controller module is employed to drive COTS battery sensors to monitor battery. This Linux kernel and our software module based BMS can be reconfigurable in the

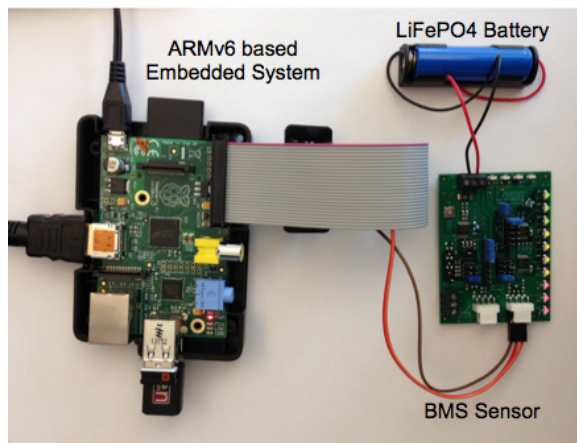


Figure 8: Battery management system (BMS) implementation

network [4]. We built the module called BMS dispatcher, which aggregates the data from the sensors and transmit it to local and remote storage.

We use SQLite for the local logging features. It is an open-source software library that implements a self-contained, server-less and transactional SQL database engine [5, 2]. For a central server side, we use MySQL database server for gathering the distributed BMS to monitor and actuate the whole BMS systems.

5. CONCLUSIONS

In this work, we address the application and management of battery storage for building energy efficiency. At the system level, we present an MPC-based algorithm to co-schedule HVAC control and battery usage to reduce energy cost, and we also conduct another study on using battery storage for EV charging and other fixed building energy loads. At the circuit level, we present a battery management system design to monitor, control and protect the battery storage system and maximize its performance and efficiency. We are currently working on integrating these elements into a holistic framework, and implement and evaluate them on our building testbed through field tests.

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