TECHNICAL FEATURE

Renewable-Powered HVAC With Thermal Storage

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Replacing or supplementing a building's heating and cooling energy requirements with renewable-powered alternatives is attractive, particularly in areas with vast renewable resources. However, regardless of the selected renewable generating method, the resources are usually intermittent. In the case of heating and cooling applications, thermal storage is an attractive and readily available technology to overcome this intermittency.

To integrate onsite renewable energy and thermal storage, a novel control strategy was implemented in the microgrid system at the Naval Postgraduate School's (NPS) Integrated Multi-Physics Energy Laboratory (IMPEL). By coupling wind and solar power generation with a control strategy that matched load demand to power generation, renewable energy (alone) was used to charge building heating and cooling thermal storage systems using an isolated microgrid. This system holds promise as both a renewable-only-based microgrid or a grid-tied system where local renewable generation is available.

The traditional electric grid provides energy to customers by matching power generation to demand. Renewable energy resources struggle to fit the current model due to intermittency, despite their potential to generate large amounts of power.[1] As more renewable energy sources become grid-tied, more large-scale energy storage is required to mitigate the variability in renewable energy production.[2,3] In heating and cooling applications, thermal loads are the main consumer of energy with the pumping of fluids, either air or water being smaller. Thermal energy storage is already commonly used for grid-tied applications and is therefore attractive for storing renewable energy where heating and cooling are the main loads.

The control theory and systems developed here can be used in two ways. The first would be in a traditional grid-tied system where local renewable energy is available and the desire is to use as much of this energy as is available. A reason for this may be that there are variable electrical rates through the day. A second reason would be the desire to have a very secure system with the ability to isolate this system from the main grid

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FIGURE 1 Energy densities of different materials: heating.[5,6]

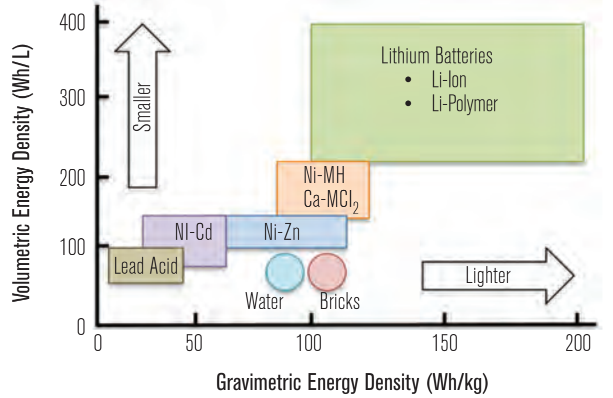
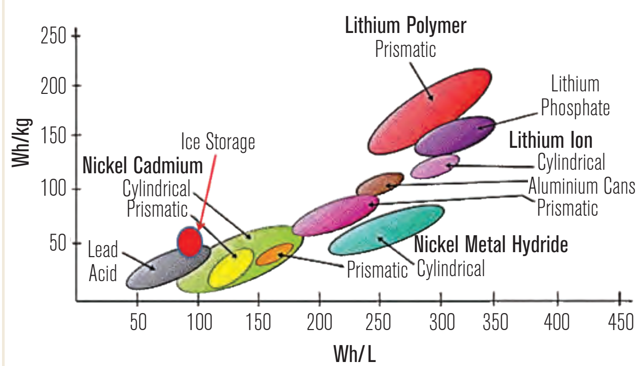


FIGURE 2 Energy densities of different materials: cooling.[7,8]



using a microgrid.[4] The control system was designed to charge the thermal storage systems by matching their load to the available renewable supply. These thermal stores could then be used by the building control system at a later stage to offset energy consumption from either the grid or in the case of isolated systems, batteries or generators.

A microgrid, or localized electric grid, usually includes a combination of power generation sources, storage devices, and loads, all of which can be grid-isolated. This independence allows microgrids to provide unique energy solutions, especially through the use of renewable power generation such as solar and wind. However, typical microgrid systems still apply the traditional energy management approach of matching power generation to load demand through the use of supplemental fossil-fuel-driven power generators. The need to provide power during peak demand, coupled with the intermittent nature of renewable energy resources, means that current microgrid systems are still dependent on electrical storage and supplemental power generation that are sized to meet this peak demand. However, adding thermal energy storage devices can reduce the size of generators and electrical storage devices such as batteries.[2]

Thermal energy storage devices present several advantages over batteries, namely, their longevity and robust nature. *Figure 1* illustrates how the thermal storage capacities of water and brick compare to the electrical storage capacity of batteries for heating applications. *Figure 2* illustrates how the energy density of thermal storage associated with the phase-change of ice compares with that of batteries. In all three cases, the actual size and masses of commercial systems were used in the calculations, which results in conservative calculations.

In the case of ice based thermal storage, extra volume is required to circulate coolant, which would have to be taken into account in a real system. Chilled water systems are also available that make use of sensible heating rather than latent, but these were not investigated here.

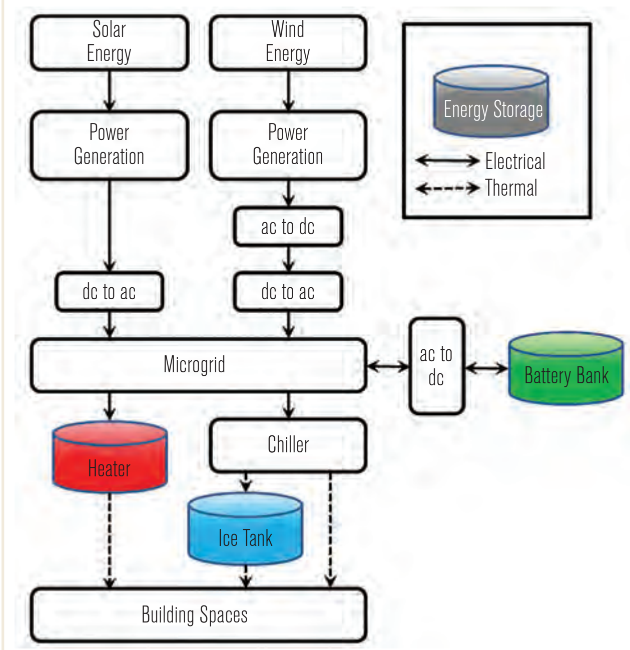
In the current study, two thermal storage systems were used. For cooling applications, an ice-based phase-change system was chosen, while for heating a brick-based sensible heat device was chosen.

As mentioned, these thermal storage devices have much longer life spans than batteries, as they can be cycled several thousand times with minimal or no degradation. Batteries have limited life spans, and their energy storage capacity decreases over time. Batteries tend to be more complex than thermal storage devices, and therefore, are generally more expensive to purchase and operate. When examining the installed cost per kWh of thermal storage, ceramic brick thermal storage is 21% cheaper than lead-acid batteries,[5,6] whereas ice storage is 73% cheaper than lead-acid batteries.[7,8]

Demonstration System

The IMPEL microgrid system was designed primarily for heating and cooling applications based on the end-use energy approach.[1] Renewable wind and solar energy provides power generation, and a three-phase microgrid transports electrical energy. This system does, however, require electrical energy storage capabilities for the control systems since it relies solely on renewable energy generation. Thus, the storage system is composed of a combination of thermal storage devices and battery-based electrical energy storage. Cold thermal storage is achieved using ice, while ceramic bricks provide hot thermal storage. Since the majority of the end-use energy is thermal, the thermal storage system accounts for the majority of the energy storage capability. The thermal storage devices can directly augment heating and cooling requirements, without the need to first convert energy from electrical energy storage. To discharge the cold ice thermal storage a coolant pump is required to circulate the fluid through the tank. Discharging of the hot brick thermal storage requires air to be blown through the bricks. *Figure 3* illustrates the energy flow of the IMPEL thermal energy system with the majority of the energy flows being into and out of the thermal storage systems. Some battery power would obviously be needed to discharge the thermal storage if renewable energy was not available. The loss of thermal energy over time was not considered, but as thermal storage manufacturers note the losses can be into the spaces that require heating or cooling.

FIGURE 3 IMPEL schematic.



Motivation

Some context is needed to explain the design of the IMPEL microgrid. The system was designed as a demonstration system but one that does offset the actual heating and cooling loads of a real building. Building 216 at the Naval Postgraduate School houses high-speed wind tunnels and so is unusual in that it has both cooling and heating requirements within a working day when operating. A brief outline of the operation of this building is needed to explain this. Air, compressed to 20 atmospheres (2026 kPa) must be cooled before it enters a large bank of 6,000 ft^3 (170 m^3) storage tanks. These tanks are later discharged to run supersonic wind tunnels in a large space. This expansion leads to very cold temperatures within the tunnel which causes the room to cool and condensation to form on the optical systems used to investigate these experiments. To prevent this condensation, heating is needed when the tunnels run. While this is a very specific building application, the use of heating and cooling is widespread, and it was thought to be an ideal forum for using renewable energy to reduce the load on the existing heating and cooling systems. An additional requirement by the wind tunnel staff was that the new renewable system could not impact its operation or availability. The actual building heating and cooling loads are much larger than the IMPEL demonstration system, which was constrained by the available budget.

The IMPEL microgrid aims to use power from renewable solar and wind resources more directly. The key is the novel control strategy that matches load demand to power generation, storing excess energy in robust and cheap thermal storage devices rather than in batteries to ultimately reduce the demand on paired, grid-connected HVAC systems. As mentioned earlier, the microgrid can easily be replaced by a grid tied solar system in cases where absolute redundancy is not required.

All of the components used for the microgrid system are commercial-off-the-shelf (COTS) equipment. Use of COTS equipment simplifies the design of the system and ensures easy reproduction. The microgrid employs a combination of wind power, generated from two 3.2 kW vertical axis wind turbines (VAWTs), and solar power from 6.4 kW photovoltaic (PV) panels. The default controls for the heating and cooling units for thermal storage were modified to allow for full implementation of the control strategy.

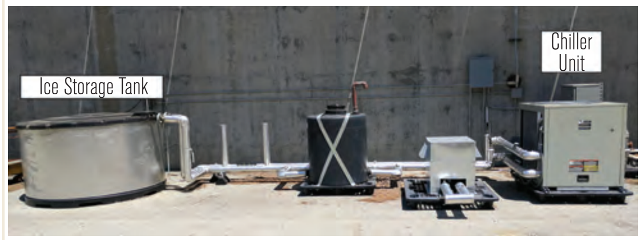
As mentioned, the system does have batteries to store electrical energy for the control electronics, coolant and air pumping and to provide additional power should it be required during the chiller startup or other transients. The power generated by the PV panels and VAWTs is supplied, through their respective inverters, to the battery bank to maintain its charge. Meanwhile, the three-phase alternating current (ac) inverters produce a 208-volt, three-phase output for running the heating and cooling units for thermal storage. The inverters can be observed in *Figure 4*. While the microgrid has the ability to be grid-tied, it was completely isolated from the main grid in this study.

The battery bank is composed of 24 valve-regulated lead-acid (VRLA) gel cells with a total storage capacity of 855–888 Ah at 48V, equivalent to approximately 11.4-11.8 kWh. While these batteries are used to stabilize the grid, they are not intended to run the loads directly for extended periods. Since the electrical capacity of the batteries is relatively small, running the chiller and heater loads from the batteries would drain them within a very short period.

Applying the end-use approach,[1] bulk renewable-generated electricity is stored as thermal energy, which can be used to support building heating and cooling requirements at a later stage.

FIGURE 4 Three-phase microgrid system.

FIGURE 5 Cold thermal storage system.



Cooling

The cold thermal storage system, shown in *Figure 5,* uses a 7.5 ton (26.25 kW) chiller with a variable speed compressor (VSC) and a variable frequency drive (VFD) pump. The chiller cools water containing 25% propylene glycol to –4°C (25°F) and circulates it through heat exchangers in an ice storage tank. The water-propylene glycol solution causes the water to freeze inside the ice tank until approximately 95% has been converted to ice. The ice tank provides 170 kWh of cold thermal energy storage (48.5 ton-hours [170 kW] of cooling). When there is a demand for cooling, a water and propylene glycol mix can be circulated through the ice storage tank, melting the ice and thus forming a heat sink. Cooling in the building or for the wind tunnel compressor is accomplished by installing a liquid-air heat exchanger between the ethylene glycol mixture and air. In the demonstration system, the mixture always flows through the thermal storage tank. The solution is diverted to the heat-exchanger before the thermal storage tank when cooling is required, forming a larger loop. While this does result in larger pump work being required this is small compared to the chiller work and results in a much simpler system. When the chiller is not running and the ice is being used as a thermal dump, the solution is simply pumped around this larger loop through the heat exchanger, thermal storage tank, and chiller.

Ice-making is known to de-rate the nominal chiller capacity by approximately 30% to 35%, which is why manufacturer intended the system to make ice at night when cooler temperatures and lower grid energy costs are found. However, since this system operates using purely renewable power, it can make ice whenever energy production exceeds demand. Additionally, the control strategy for this project prioritizes the chiller for direct cooling of building spaces first, which would be conducted at a higher thermodynamic efficiency. Once the required cooling load is met, the chiller then generates ice for thermal storage if renewable energy is available. But, this does cause the chiller to operate in a less efficient mode during conventional operation as its setpoint is kept at a point suitable for ice production. A system based on chilled water would require a larger thermal storage volume but would potentially be more efficient as the cooling would take place over a smaller temperature difference. The chiller would also not have to be de-rated to the same extent. At the time of writing, the final cooling loop to the building compressor outlet had not been completed, but this did not prevent the thermal charging algorithm from being evaluated.

Heating

The hot thermal storage system is a ceramic brick, forced-air heating system, as shown in *Figure 6.* The heater was designed to store off-peak electricity in the form of heat, similar to the cold thermal storage system. The integrated heater converts electrical energy into thermal energy within an insulated ceramic brick core. Since electricity is converted to heat within the insulated core, the energy conversion is theoretically 100%. The heater is capable of reaching temperatures up to 650°C (1200°F), which provides 120 kWh of hot thermal energy storage (409,440 Btu [432 MJ] of heating).

When there is a demand for heat, a fan blows air through the ceramic bricks, which then heats the space that requires heating. Additionally, locating this system inside or under the space to be heated ensures residual heat loss is not wasted, further increasing system efficiency. The heating system discharge into the space has been operated using the systems built in fan. The only modification to the unit was the addition of an inlet filter.

Thermal Losses

It was outside of the scope of this study to measure the loss to the surroundings but both technologies are in commercial use typically assuming a 24-hour cycle. It is not known what their effectiveness over a multi-day period would be. Compared to the ice thermal storage the temperature difference between the ceramic bricks and the surrounding is much larger and the manufacturers recommend placing these devices within the space that is to be heated.

Control

To implement the desired control strategy, communications had to be established between a centralized controller and the equipment. The controller was designed and implemented using the programming language MATLAB.

A challenge in designing a system such as this is that each component may use different communication and control protocols; each must be accessible by the central controller. A USB serial port adapter is used to communicate with the heater system, the Modbus protocol over Ethernet is used to communicate with the microgrid inverters, and an analog output device is used to vary the chiller power. A BACnet communication protocol over Ethernet to communicate with the chiller system is also possible. The different communication protocols are often fixed by the particular industry, and it is hoped that consideration of this fact will be made by manufacturers in the future.

MATLAB was used to develop functions that could execute each of these communication protocols. A separate function was developed for each protocol. *Figure 7* shows the basic strategy used to control the system. The prioritization of the loads can be modified depending on the season.

The overall objective of the control strategy is to match the chiller and heater load demands to the available power being generated from the renewable resources without requiring additional power from the batteries. By matching load demand to power generation, the system uses all available power from the renewable energy resources. In the current application the aim was to charge the thermal storage systems as much as possible while in a more conventional system, excess thermal energy, not immediately needed for heating or cooling applications, would be stored.

FIGURE 6 Hot thermal storage system.

System Operation

The microgrid controller was developed and implemented in January 2016 using MATLAB software. The MATLAB code used for this work is available upon request. The system ran continuously for six months, collecting data. These data provided the information necessary to update the controller to improve inter-device communications, as well as overall system performance. Operation of the controller is monitored from a desktop computer and allows the user to actively monitor the status of power generation, load demand, and energy storage levels. These data update in near real-time, with every iteration of the control loop, and ensure the user is kept abreast of controller performance and system operations.

Thermal storage percent of completion (POC) was used to prioritize the heater and chiller load demands. POC is set by the user or other decision making system depending on the anticipated heating of cooling loads. The controller then adjusts the loads based on current storage levels. On a practical note, there is usually a lower limit for the part-load operation of chillers, 20% in this particular system. If there was not enough power to meet this criteria, the energy was diverted to the heater.

Figure 8 shows an example of control data collected on May 22, 2016, which was mostly sunny. The controller never prioritized the chiller as ice storage levels never dipped below heater storage levels, and the user preference for storage levels was set to the same value. A very conservative approach to preserving the battery life in the microgrid was used. During the early morning period, the batteries enter a so-called, "boost phase," where they are recharged following the previous night's energy drain. While the batteries were in this state, the chilling and heating systems were not used.

The interpolated maximum potential power generation is shown by the dashed line. The area between the dashed line and the solid line, denoted by "Unused Energy," represents energy that can run the chiller and heater. The objective of the control strategy is to prevent unused energy such as this. Theoretically, loads could have been introduced to use the excess power and ensure the batteries receive all the power they can accept during their "boost phase." This is not an ideal strategy for making best use of the power available but the microgrid used did not allow enough visibility into the internal power flows to know whether using power would reduce the maximum, 'boost' charge to the batteries. Preserving the batteries and making sure they were fully charged before running the thermal charging system was the approach taken. When choosing a microgrid, the ability to communicate with it and have access to its internal operating conditions is an important consideration.

Once past the boost phase the control strategy was designed to match the chiller and heater loads to the available renewable energy as closely as possible. The aim was to charge the thermal storage systems as effectively as possible while preserving the batteries. In a system where either grid power or backup generation is also available, these resources could also be used to ensure the thermal storage levels were high enough to ensure sufficient cooling or heating. Reindl[3] presents such a scenario for a wind and grid-powered cooling system with thermal storage.

Figure 8 shows that the desired control strategy was successfully implemented. The microgrid controller was able to match load demand to power generation,

FIGURE 7 Microgrid control loop.

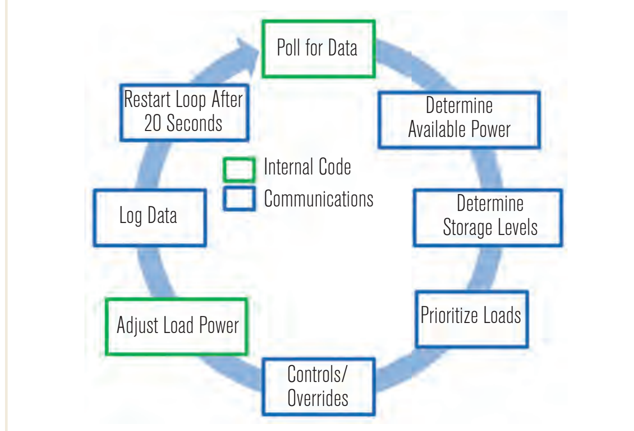
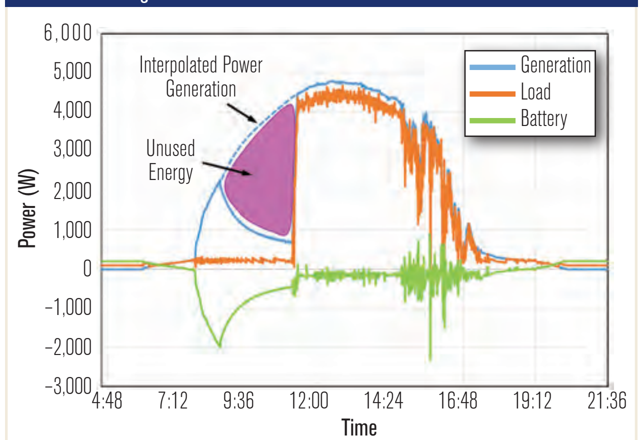


FIGURE 8 Microgrid control results.



without requiring the batteries to run the loads. Thus, the batteries are only used to cover brief periods when load demand exceeds power generation, as well as for microgrid stabilization at night when there is only wind generation. MATLAB allowed for easy implementation and modification of the microgrid controller.

Grid-Tied Operation

Many building operators that have onsite renewable generation capabilities do not have a microgrid, but this does not mean that the control strategies outlined here could not be used. In these cases, real-time energy consumption data from the utility meter would be used instead of data from the microgrid. A number of factors could drive such a control strategy: net-metering agreements, variable electrical tariffs during parts of the day, and a potential difference in price between the amount paid to a customer for power added to the grid and their consumption. Any of these factors would make it more attractive to use this power locally, while available, to charge thermal storage devices. A thorough investigation of these concepts is outside the scope of this study, but the control strategy and systems presented here can easily be modified to lower heating and cooling energy costs.

Conclusions

Data collected and presented demonstrated that the microgrid system can successfully match load demand to within 5% below and 1% above power generation by using thermal storage under normal conditions. The ability to finely adjust load power was a vital part of implementing the control strategy, as the controller was required to manipulate the demand from the heater and chiller to match the renewable power available. This is simple to perform using modern variable power controllers for both the heating and chilling systems.

The decision to use commercial-off-the-shelf components shows that current components are adequate for the task of using renewable energy to charge thermal storage systems but certain shortcomings were evident. To be more effective there must be better communication with microgrids. No simple method could be found to charge the thermal storage system while the batteries were in their, "boost," charging phase. A simple register that showed whether or not they were being charged at their maximum rate or not would suffice. Current thermal storage systems are designed to operate on a daily cycle and very little information is available as to their thermal heat loss rates. Quantifying how much energy can be stored over a number of days would make their use in renewably powered systems more attractive. Finally, a personal computer was used to implement the control system which simplified development. However, an industrial, programmable logic controller (PLC), would be a more robust method of implementing any control strategy.

While the main aim of control strategy used here was to charge the thermal storage by matching demand to available renewable supply, the demonstrated microgrid and storage system can easily be operated to achieve other purposes. As mentioned earlier, satisfying immediate cooling and heating loads before charging the thermal system would be the usual approach in a conventional building. If reasonable forecasts of the required thermal loads were known then the thermal charge levels of the system could be set. These type of requirements would be simple to add to current control strategy. The control strategy could also be implemented on a grid tied system where renewable sources of power are available.

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