

DESIGN AND MODELING OF DISPATCHABLE HEAT STORAGE IN WIND/DIESEL SYSTEMS

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ABSTRACT

This paper discusses a heating system designed to increase the utilization of wind power in cold climate wind/diesel systems where a seasonal mismatch exists between the wind resource and the conventional electric load. The heating system consists of dispatchable electric space heating units, with integrated thermal storage, functioning as distributed heat loads. Control issues are analyzed using a 1 Hz time-series model. Separately, the Hybrid2 computer code has been adapted to effectively model the heating system's long-term performance and is applied to a specific case in New England.

1.0 INTRODUCTION

In New England's off-grid island communities, the summer electrical load is often significantly greater than the winter load due to larger summer populations. A typical example in New England is Cuttyhunk Island, where summer population reaches over one hundred while only twenty-five residents inhabit the island year-round. Figure 1 shows how the electrical load increases significantly over the summer months on Cuttyhunk (O'Donovan 1993).

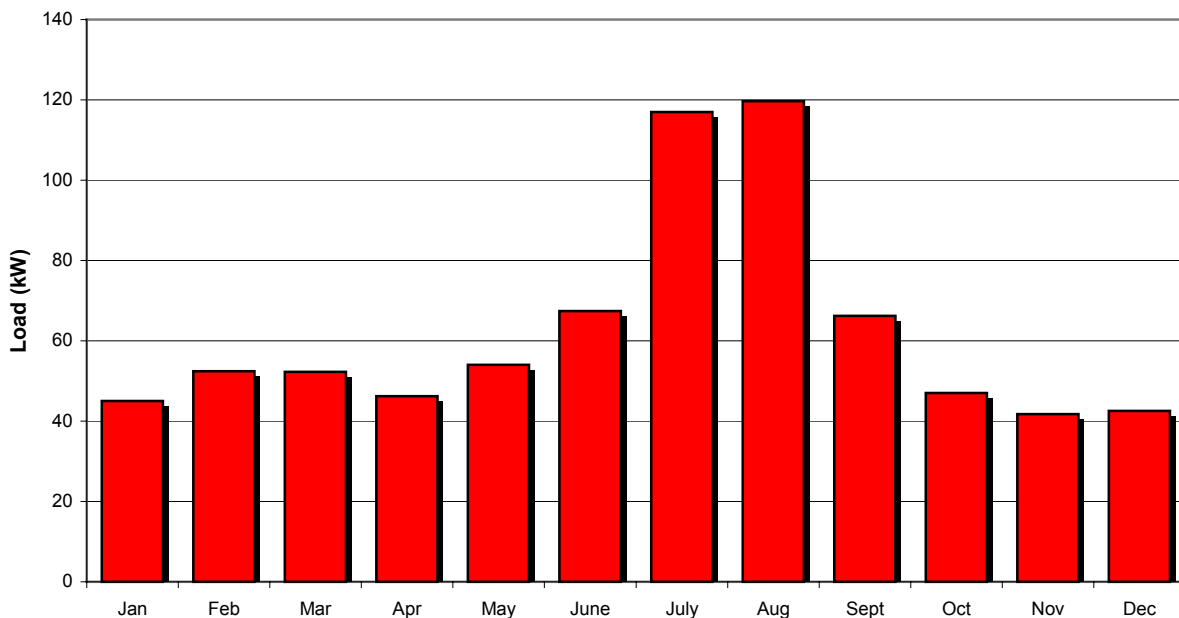


FIGURE 1: AVERAGE MONTHLY ELECTRICAL LOAD ON CUTTYHUNK ISLAND

New England also has an excellent coastal wind resource. However, the annual profile of New England's wind does not follow the trend of the electrical load; the winds are generally higher in

the winter. Figure 2 shows how the wind resource on Cuttyhunk Island peaks during the winter months (O'Donovan, 1993).

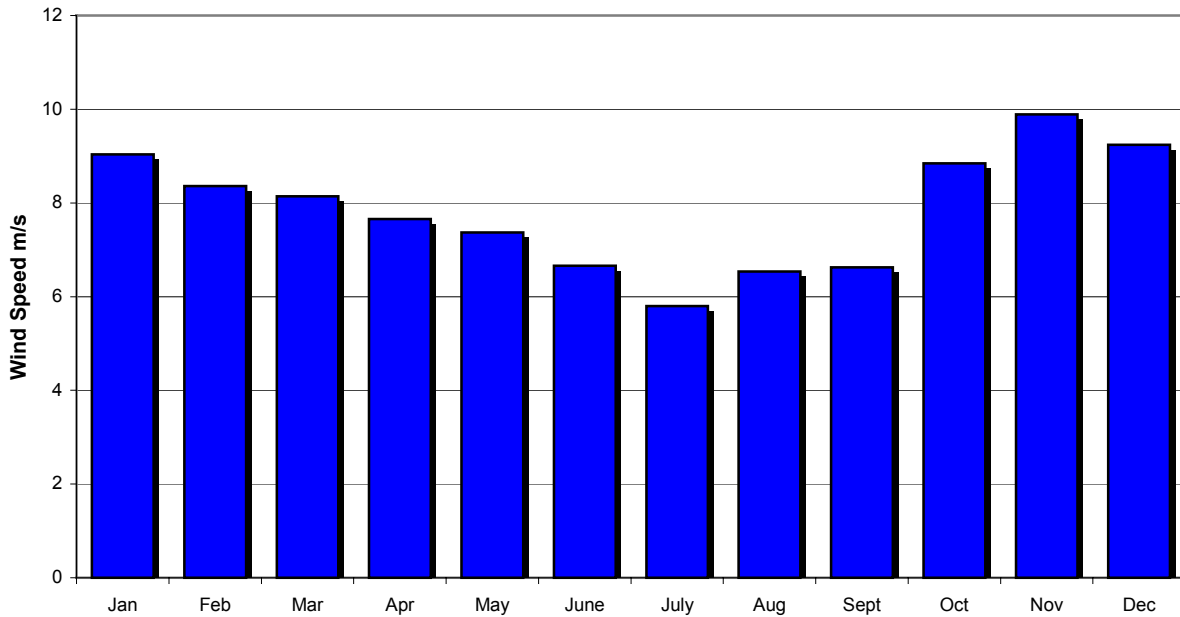


FIGURE 2: AVERAGE MONTHLY WIND SPEED ON CUTTYHUNK ISLAND

This seasonal mismatch between available wind and load occurs in many isolated cold-climate diesel systems around the world where the summer population is greater than number of year-round inhabitants. New England has over one hundred off-grid power systems of various sizes that exhibit a mismatch between wind resource and electrical load (Manwell, 2002).

Although there are currently no wind/diesel systems in New England, there have been numerous studies and efforts to design and install wind/diesel systems on islands in New England (O'Donovan, 1993; Rogers, et al., 1998; Manwell, et al., 2001). Cuttyhunk and Block Island were some of the important early wind/diesel systems installed in New England (McGowan, et al., 1988). The issue of matching wind power with load creates a fundamental issue for designers of wind/diesel systems in New England. A wind/diesel system designed to achieve high wind power penetration in the summer will be over-sized in the winter and produce a surplus of wind energy. On the other hand, if the turbines are selected to meet the winter load, the system will be under-sized in the winter and will reach only a modest average penetration.

To make wind/diesel systems more economic in New England and other areas that experience the wind/load mismatch, designers need to find an effective long-term storage medium or end use for the excess power produced during the winter. For large wind/diesel systems (>100 kW rated wind power), long-term reusable electric energy storage is generally considered to be uneconomical. End uses, such as heating and water pumping are certainly attractive and may be economic; while others, such as hydrogen and desalination are intriguing and worth further study.

In cold climate systems, thermal loads are perhaps the most obvious solution, because the excess power would otherwise have to be dumped as waste heat. Numerous concepts for

using heat with varying degrees of sophistication have been proposed and implemented (Hunter and Elliot, 1994; Drouilhet, 1999). Most of the designs involve using the waste heat from the dump load directly for hot water or space heating to meet a large, single thermal load (Mott, 1999). For such systems, these heating concepts have been able to utilize surplus wind energy.

However, in many regions the heating loads are often distributed throughout the system in residential buildings. An effective heating system for these situations must evenly distribute the excess wind power to the heating loads. The conventional dump load does not allow for feasible use of the waste heat over areas larger than a building. A central heating system with hot water storage is frequently difficult to install in an existing community where another form of heating is used. A conventional electric space heating system will not be successful unless the individual heating units in the system can be controlled.

This paper describes the design of a dispatchable heating system designed to meet a portion of distributed residential heating loads while increasing the amount of productive wind energy. The heating system consists of individually controllable, electric space heating units with thermal storage. They are intended to supplement an existing heating system. A control and communication scheme to realize this dispatchable heating system is explained. Control issues are analyzed using a one Hz model that simulates the heating system within a generic wind/diesel system. The purpose of the model is to test how well the heating system distributes the surplus energy and to quantify the amount of excess energy that could be utilized for heating.

This dispatchable heating concept originated from efforts to design a wind/diesel system on Cuttyhunk Island. The Renewable Energy Research Laboratory (RERL), under the support of the Massachusetts Division of Energy Resources, recently produced a feasibility study that uses the Hybrid2 simulation tool to model the long-term performance of wind/diesel system options for Cuttyhunk. The results of this study are summarized in this paper, with particular attention given to the potential economic benefits of including dispatchable heat storage within the wind/diesel system.

2.0 DISPATCHABLE HEAT STORAGE SYSTEM DESIGN

This section describes a proposed load control strategy and the requisite hardware configuration for a dispatchable heat storage system within a wind/diesel system. The fundamental objectives of the heating system are to: (1) increase the amount of economically useful wind energy, (2) save heating fuel, (3) maintain quality of primary load.

The concept of controllable distributed secondary loads as a method to dump excess power usefully in wind/diesel systems has existed for several years (Hunter and Elliot, 1994). The basic idea is to activate or shed the distributed loads individually as the excess power varies. Control is typically the main issue for implementing dispatchable distributed loads, because the challenge is to vary the load to match the available power.

Switching distributed loads requires some command to be transmitted from a location in the system where the available excess power is known (i.e. the dump load). In its simplest form, the command should switch a relay to enable or disable the load. This necessitates: (i) for each controllable load a controller with some form of intelligence located near the load to receive and process the command, (ii) a central controller with knowledge of the excess power to create and transmit the commands. There are a number of factors that influence a detailed load control strategy for a particular application, including:

- Type of load (i.e. space heating, hot-water heating, water pumping)
- Number and location of the loads on the system
- Existing communication carrier infrastructure (i.e. phone line, cable)
- Expected profile of excess power

2.1 Description of Electric Thermal Storage Heaters

In order to smooth the fluctuations in the excess power and provide a more consistent heating power output for the user, electric thermal storage (ETS) heating units can be used. They are resistance heaters with electric elements encased in ceramic blocks (Figure 3). They are commercially available space heating units designed for individual rooms and equipped with thermostats and fans to dispense the stored heat. Reaching temperatures around 675° C (1250° F), they can provide several hours of thermal storage, depending on the size and rated output of the heater. Table 1 provides an overview of the important specifications of ETS units from one manufacturer (Steffes Corporation). All heaters listed have a nominal input voltage of 240 V.

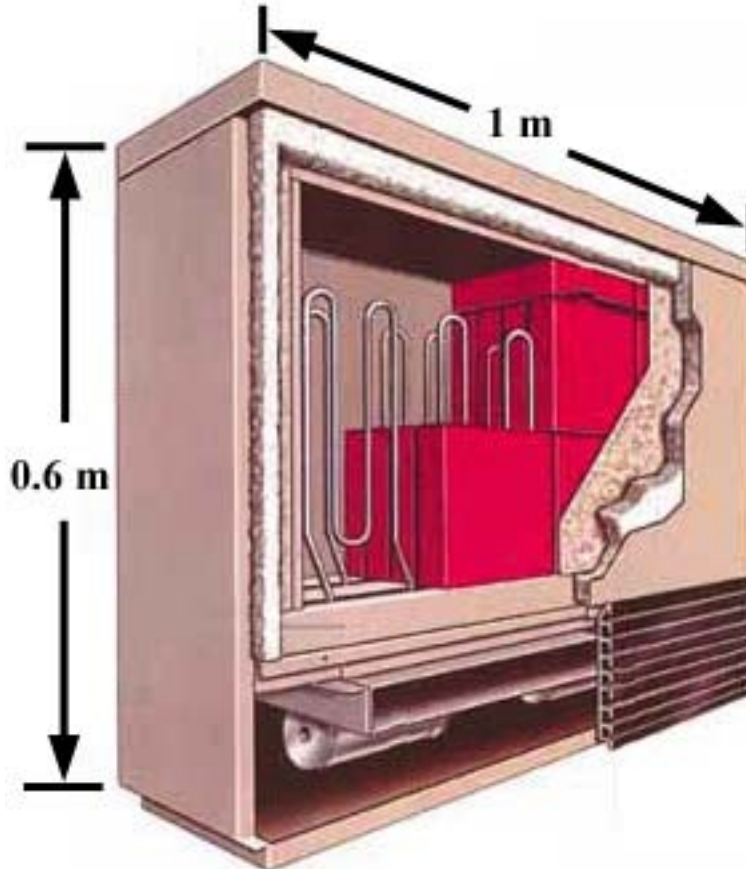


FIGURE 3: SCHEMATIC OF ELECTRIC THERMAL STORAGE HEATER
(www.skrecc.com/ets.htm)

TABLE 1: EXAMPLE CHARACTERISTICS OF THERMAL STORAGE HEATERS
(www.steffes.com)

Input Power kW	Storage Capacity kWh	Max Heat Output kW	Dimensions m	Installed Weight lbs (N)
2.4	13.5	3.5	0.76 x 0.62 x 0.27	267 (1188)
3.6	20.3	4.3	0.94 x 0.62 x 0.27	376 (1673)
4.8	27.0	5.8	1.12 x 0.62 x 0.27	478 (2126)
6.0	33.8	6.2	1.30 x 0.62 x 0.27	585 (2602)
7.2	40.5	6.5	1.47 x 0.62 x 0.27	692 (3078)

The ETS heaters are used frequently by customers of electric cooperatives and other utilities that have time-of-day rates. The utility typically sets a period of the day when the heaters can recharge, such that storage is replenished during off-peak hours. In wind/diesel systems, the thermal storage would recharge when the dump load is sufficiently large to supply the necessary input power of the heater. The aim of the thermal storage is to deliver more consistent heat for the user while smoothing the fluctuations in the excess power. The methods for accomplishing this load management technique are described in the next sections of this paper.

2.2 Control Architecture for a Dispatchable Heat Storage System

As mentioned above, the heating units in this proposed system are distributed in individual homes and buildings throughout the system network. A central controller broadcasts a single data string throughout the system detailing which loads should be switched on or off. All of the distributed load controllers receive the data, and those that are selected switch a relay to the heater based on the instructions in the data. Figure 4 shows a two-line schematic of the control architecture, with the details given below.

The total rated input power of all the heaters on the system should be sized to roughly match the maximum expected excess power and the total heating demand of the system users. In order to maximize the amount of usable excess power, it is preferable to dispatch the heaters incrementally as the excess power fluctuates. The smaller the rated power of the dispatchable increments and the more of them, the better the system will be at matching the excess power. For the heating units considered in this report, the smallest input power is about 2 kW (Table 1). The number of users on the system limits the number of heaters that can be distributed. Furthermore, since the amount of data in one broadcast increases with the number of distributed loads to control, the number of heaters is limited by the data rate capabilities of the communication system.

The communication system's data rate also restricts the rate of switching the heaters on and off. Ideally, heating units would be dispatched immediately whenever excess power was available. For a heating system with several distributed heaters, this would require very high speed communication (>56 kBaud), which is likely not economical nor physically practicable for wind/diesel systems. Furthermore, the frequency of switching must be within the capacity of the relay on the distributed load controller. For the heating system designed in this report, one Hz switching is achievable, although a slower rate may be more practical. This dispatchable heating system does not aim to control high frequency power fluctuations. A conventional dump load should be used for that purpose.

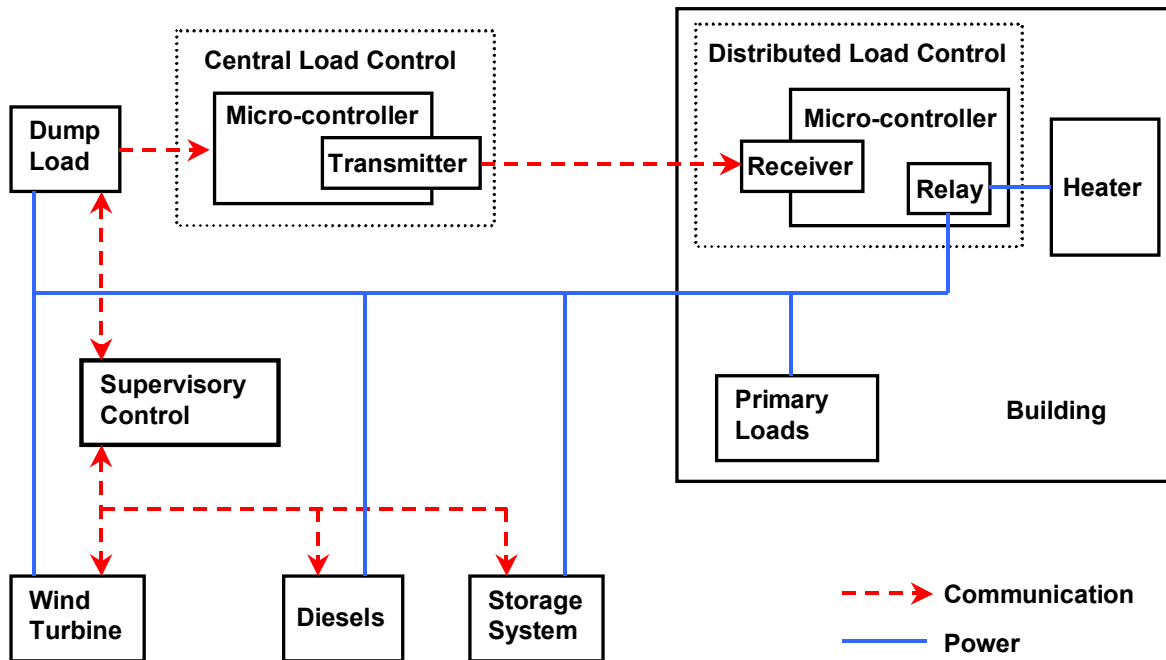


FIGURE 4: DISPATCHABLE HEAT STORAGE CONTROL DIAGRAM

In order to make the heating system equitable, priority for receiving excess power should be varied. All users are assigned a priority level that is shifted on command from a central controller. In this manner, the heaters with the highest priorities would be the first in line to receive power when it becomes available. The distributed load controllers must therefore be capable of interpreting a priority level signal and storing it in memory. The time-step for priority shifting depends on the number of priorities to assign and the desired length of time over which the energy received by each user should be equal. For instance, if energy is to be evenly divided over one day, the priority levels need to make a complete cycle in one day. Additionally, the rate of priority shifting should be low enough to allow the heater to obtain a useful amount of energy and should be no higher than the assumed heater on/off switching rate. It is assumed that multiple heaters within one building or residence would be assigned the same priority, so that priority level is based on the user rather than the heater. This strategy may not be appropriate in situations where large community facilities such as schools exist. In such cases, it may be preferable to assign priority to each heating unit.

The dump load controller initiates the process of enabling or disabling the heaters by sending a signal of the excess power to the central load controller. The central load controller uses the excess power signal to decide how many heaters may be activated or how many must be turned off to maintain the power balance of the wind/diesel system. The power available for heating is the system's excess power minus some safety limit, which is the minimum amount of power that the dump load must dissipate before excess power can be dispatched for heating. Thus, when the excess power has reached a level above the defined safety level, the central load controller may dispatch heaters. Conversely, when the excess power falls below the safety level, the central load controller must shut off heaters.

The dump load sends the excess power signal continuously (high speed communication), but the central load controller only delivers signals at a defined time-step (probably not higher than 1Hz). In this design, the central load controller broadcasts one data set to all distributed load controllers. Each distributed load controller receives the data and must interpret whether the command is intended for it, based on its priority level setting. For instance, if the central load controller sends a signal for three heaters to switch on, the three distributed load controllers with the highest priority settings would each switch a relay to activate a heater. The central load controller may bundle the on/off command with a priority shifting command and transmit the two commands as one signal. If a distributed load controller does not correctly receive or process the priority level command, then some users may end up with the same priority level and the system would not function efficiently (i.e. multiple heaters could be activated at once when the central load controller intended to activate one). Therefore, once a week (or month) the central load controller will broadcast an initialization signal that redefines the priority level of all users on the system. The initialization signal can also be used when new heating users are added to the system. In emergency situations – when all of the distributed loads must be shed – the central load controller sends one signal immediately commanding all heaters to switch off. In summary, the possible signals to be broadcast by the central load controller are:

- On/Off Command only
- On/Off Command and Priority Shift Command
- Initialization Command
- Emergency Off Command

The increase or decrease of the excess power as heaters come on or offline provides feedback to the dump load, which then updates the central load controller. The central load controller retains knowledge of how many on/off commands it has sent and the number of distributed load controllers on the system. It also must know the rated input power of the heater used in the system in order to dispatch the correct number of heaters. For example, if at a certain moment the available power for heating is 20 kW and the heaters selected for the system are rated at 4 kW, the central load controller must send a signal commanding 5 heaters to switch on. If the excess power suddenly drops by 8 kW, the central load controller must then command 2 heaters to switch off.

The control strategy described above is intended to work for electric resistance heaters with or without thermal storage. The users retain ultimate control over the individual heaters in their home or building. User control of the thermostat may limit the amount of excess power that can be utilized. However, with the addition of thermal storage the heaters can be enabled to recharge regardless of whether the facility demands heat at a particular time. It should be noted that while the approach discussed is the simplest and most practical so far, a power electric switch could be developed that could control power flows more smoothly.

2.4 Dispatchable Heating System Hardware Components

Due to the narrow focus of this application, there are a limited number of hardware options available to realize the described control strategy. Nevertheless, the heating system has been designed so as to not exclude any potential hardware. The following list summarizes the control system components for which hardware is required (see Figure 4):

- Central Load Controller
 - Communication Broadcaster
- Distributed Load Controller

- Receiver (Modem)
- Relay
- Communication Carrier

There are two basic options for both the central and distributed load controllers: (1) micro-controller and (2) Programmable Logic Controller. Micro-controllers – software programmable, single board computers – are preferred because of their low cost and flexibility. Each load controller would have one micro-controller to process incoming data and execute commands. The protocol used by the micro-controllers is flexible.

The control strategy explained in the previous section calls for digital communication between the central load and distributed load controllers. Approximately 1 byte is required to provide information to one distributed load controller. Additionally, the initialization command – a more complex signal – necessitates probably 2 bytes per distributed load controller. Thus, if a system has 30 distributed load controllers, the communication system should be capable of transmitting approximately 100 bytes of data per broadcast. At one broadcast per second, the required data rate is then 100 bytes per second (800 Baud).

The type of transmitting and receiving hardware depends on the communication carrier. There are several options for a communication carrier:

- Wireless Radio
- Powerline Carrier
- Cable
- Fiber Optics
- Telephone line

Cable, fiber optic, and telephone lines currently offer the best data rates but are expensive to install. In most isolated diesel systems, the existing communication infrastructure is limited and these lines often do not exist. Furthermore, when these carriers are present, using them for the heating system communication could pose potential conflicts with the existing service provider (phone company). However, installing new lines could provide high speed internet service to the area, in addition to serving the heating system.

Utilizing the existing power lines has potential because the necessary infrastructure is already in place. Ripple control has been used for many years by utilities for load management applications. However, issues arise when signals are sent across distribution transformers. To pass through transformers, ripple technology uses high power signals that can only perform crude functions. There are a number of companies developing power line communication for high speed data transmission, but the technology is still in the prototype phase.

Wireless radio offers a simple and robust option for the heating system network. Radio frequency transceivers (modems) can transmit and receive digital signals over several miles with data rates of 100 KBaud. Current radio communication technology uses spread spectrum modulation on the UHF band. Radio transceivers can be used for both the central load controller broadcaster and the distributed load controller receiver. They would interface with the load controllers via an RS-232 serial port or TTL level. Each transceiver uses an antenna to broadcast or receive signals. The size and location of the antennae depend on the type of transceiver used and the distance between the central load controller and the distributed load controllers.

In order to switch the heaters on and off every second, high speed solid state relays are required. The relays must also be capable of handling up to 40 amps.

3.0 MODELING OF DISPATCHABLE HEATING SYSTEM CONTROL

A time series computer model of wind/diesel systems with dispatchable heat storage has been written to test the control strategy described in the previous sections. The program was envisioned to analyze a proposed wind/diesel system on Cuttyhunk Island. A brief description of the model and results from various simulations for the proposed Cuttyhunk system follow.

3.1 Description of Dispatchable Heating System Control Model

Using the control algorithm outlined above, the model attempts to test the effectiveness of a dispatchable heat storage system. Specifically, the model seeks to: (1) determine how equitably the system distributes the excess power to the heaters, (2) quantify the utilization of the excess power towards heating, and (3) estimate the percentage of the total heating load served by the dispatchable heating system.

The model requires the following inputs:

- Time Series Data
 - Wind Speed
 - Primary Load
 - Temperature
- Wind Turbine
 - Number of Turbines
 - Rated Power
 - Power Curve
- Diesel Generator
 - Number of Diesels
 - Rated Power
 - Fuel Consumption Curve
 - Minimum Run Time
 - Minimum Power Level
- Dump Load
 - Rated Power
- Dispatchable Heater
 - Number of Heaters
 - Input Power
 - Storage Capacity
 - Output Power
 - Heat Loss Coefficient of Area to be Heated – for Heating Demand
- Heating System Control Inputs
 - Minimum Power Level to Activate/Deactivate Heaters
 - Maximum Rate of Activating Heaters
 - Frequency of Heater Priority Shifting

The time series data should be representative of the site characteristics of the proposed wind/diesel system's location.

Every heater on the system is assumed to have an identical heating demand to meet. The calculation of the heat load is based on a typical home's heating fuel consumption for the climate zone in which the wind/diesel system would reside. From the fuel consumption, a representative heat loss coefficient per residence is calculated. However, one ETS heater cannot meet the entire demand of a typical home in most cold climate zones, such as New England. Therefore, the heating load that each heater attempts to supply in the model is less than the total heating load of a residence. This is accomplished by reducing the heat loss coefficient. The time series heat load of each heater is then found by multiplying this reduced heat loss coefficient by the outdoor ambient temperature.

In this program, intermittent diesel operation is permitted. However, neither short-term reusable electrical energy storage nor other components to provide reactive power is modeled in this program. It is assumed that any short-term electrical storage – on the order of 1 minute at the average electrical load – would not significantly alter the amount of excess power available for heating.

The wind power is used first to meet the primary load. Any shortfall is covered by the diesels. Excess power is calculated by the difference between the sum of the diesel and wind power and the primary load. Any excess power above the minimum power level for heater activation is available for heat. The heaters on the system share this excess power based on their priority level. If the excess power exceeds the heat load, it is put towards storage. When the storage capacity is reached, the remaining power is dumped through the dump load. The code outputs the following time series data:

- Wind Power
- Diesel Power
- Diesel Fuel Consumption
- Heating Demand for each Heater
- Excess Power Input into each Heater
- Output Power of each Heater (Heat Load Served by each Heater)
- Heater Storage Level
- Excess Power Dissipated in Dump Load

From these outputs, the system designer evaluates: (1) how evenly the excess power was distributed amongst the heaters on the system, (2) the utilization of the excess power towards heating, and (3) the portion of the total heating load served by the dispatchable heating system.

3.2 Dispatchable Heating System Control Model Results

As mentioned previously, this model was designed to test a dispatchable heating system for Cuttyhunk Island. Simulations described in this report use system components that are sized to match characteristics of Cuttyhunk. The proposed wind/diesel system on Cuttyhunk Island is described in further detail in section four of this report. Several input parameters were varied in the simulations to evaluate the effects of three main variables: (1) the amount excess power available for heating, (2) the heating load, and (3) the heating capabilities of each dispatchable heater.

All simulations use a complete day of one Hertz time series data. Two different sets of data were used to represent a day in mid winter and a day in the fall or spring on Cuttyhunk Island. All data sets were synthesized using the autoregressive moving averages technique with mean values taken from real data on Cuttyhunk (See O'Donovan 1993 or Manwell, et al., 2001 for

information pertaining to the Cuttyhunk data). These data sets are modeled on extreme cases of fluctuations in order to analyze worst-case scenarios. The table below lists the statistics of these input data sets:

TABLE 2: STATISTICS OF INPUT DATA SETS FOR CONTROL MODELING

Data Set		Average	Standard Deviation
Winter	Wind	9 m/s	5
	Primary Load	45 kW	5
	Temperature	0°C	1
Fall/Spring	Wind	7 m/s	4
	Primary Load	60 kW	5
	Temperature	7.5°C	2

The next table gives a short list of input parameters used for the simulations described in the report. Multiple values indicate that the inputs were varied over different simulations.

TABLE 3: INPUT PARAMETERS FOR CONTROL MODELING

	Parameter	Value
Wind Turbine	Number of Turbines	1
	Rated Power	50, 100, 250 kW
Diesel Generator	Number of Diesels	2
	Rated Power	115 kW
Dispatchable Heaters	Number of Heaters	16, 32
	Rated Input Power	1.5, 3 kW
	Storage Capacity	13.5, 20 kWh
	Rated Output Power	1.75, 3.5 kW
	Heat Loss Coefficient	0.044 kW/°C
Heating System Control Inputs	Minimum Power Level to Enable Heaters	10 kW
	Maximum Rate of Activating Heaters	1 min, 5 s, 1 s
	Priority Shifting Rate	1 hr, 15 min, 1 min

The results from all simulations indicate that equal distribution of the excess power is readily achievable if the following condition is met: the priority levels must be shifted often enough to rotate the priorities through one complete cycle over the desired length of time. For instance, if equitable distribution is required after one day and there are 16 heaters on the system, the priority levels should be switched at least 16 times over the course of the day. The maximum rate at which the heaters can be turned on does not affect the equal distribution of the excess power throughout the network, provided the activation rate is faster than the priority shifting rate.

Three main factors influenced the amount of excess power used for heating: (1) wind turbine rated power, (2) heater quantity and rating, and (3) the rate at which the heaters are cycled on and off. The amount of available excess power varied significantly with the size of the wind turbine. Systems using a 250 kW wind turbine generated three times the amount of useful energy for heating in the winter and five times in the fall/spring compared to systems with the 50

kW turbine. Intuitively, a larger wind turbine will produce more excess power for a given primary load. Also for systems with the 250 kW turbine, the number of heaters and their rated input power and storage capacity greatly affected the useful wind power. For example, doubling the heaters from 16 to 32 doubled the amount of useful excess energy. For systems using either a 50 kW or 100 kW turbine, increasing the heating capacity of the system did not increase the amount of excess energy used for heat because the systems were already limited in excess wind power.

The main purpose of this model was to test the control aspects of the heating system rather than the sizing of components. The control parameters selected for modeling are based roughly on the size of the proposed system and the physical limitations of the control hardware. The minimum power level above which the heaters can be turned on is intended to be large enough to account for the rapid fluctuations in the primary load and wind power. The maximum rate at which the heaters can be switched on and off was chosen based on capabilities of available control and communication hardware. The results show that the faster the heaters can be switched, the more excess wind energy can be utilized for heat. Although results are still preliminary at this point, increasing the on/off switching time step from 5 seconds to 1 second shows a three fold average increase in usable excess energy. Further testing with different inputs should be completed to obtain a more comprehensive understanding. It is also important to note that the frequency of priority shifting does not affect the total amount of useful excess power delivered to the heating system. However, this may not necessarily be true in a real system where individual preferences can dictate use of the heating system (i.e. heating loads of residences are not identical in a real system).

The heating demand naturally has a significant influence on how much excess power can be used for heat. In this model, the heat loss coefficient used for the heat demand calculation is 25% of the heat loss coefficient of a single residence on Cuttyhunk Island. In other words, it is assumed that one heater can supply at most one fourth of the total heat load of a residence. This simple approximation might not be adequate in all situations. Certainly, larger heaters should be capable of fulfilling more of the heat load. Furthermore, the model assumes that the equivalent heat load of each heater fluctuates continuously with the outdoor ambient temperature. In reality, heating systems probably operate more discretely – turning on for a short time to bring the room temperature to a certain user-defined temperature. A more sophisticated model for how much of a building's total heat load an individual heater can supply and how the heat load varies with time might be more appropriate.

4.0 LONG-TERM PERFORMANCE MODELING ON CUTTYHUNK ISLAND

The wind/diesel system modeling program, Hybrid2 (Manwell, et.al. 1998), has recently been modified to simulate heating loads with thermal storage. This version will be available shortly from NREL. It is used in this study to evaluate the economic feasibility of wind/diesel systems with dispatchable heat storage. The design options and the results of the Hybrid2 modeling are presented in this paper.

4.1 Cuttyhunk Island Site Characteristics

Cuttyhunk Island is about 2.5 miles long and 0.5 miles wide and situated fourteen miles off the coast of New Bedford, Massachusetts. The twenty-five year-round residents on the island and the couple of hundred summer residents make up the majority of the Town of Gosnold, which compromises a few other islands in the vicinity. There are residential dwellings, a one-room schoolhouse, a library, a town hall, a church, a fire station barn, one grocery store, two restaurants, and two harbor/marina buildings on the island. It has no industrial or energy-

intensive commercial activities. The small marina harbors a few local fishing boats year-round and many recreational boats during the tourist season. The town's municipal utility operates the island's generation facilities (4 diesel generators) and the 480 V, 3-phase distribution system.

One year of hourly wind speed, electrical load, and temperature data from a previous study initiated by US Windpower and completed by RERL (O'Donovan, 1993) were used in this paper. As described previously, Cuttyhunk experiences a substantial temporal mismatch between the available wind resource and the primary electrical load (Figures 1 and 2). The average wind speed through the winter months on Cuttyhunk is 8.9 m/s, while the summer months have a mean wind speed of 6.3 m/s. The annual average of the primary load is 60 kW, but the hourly load peaks at near 300 kW in the summer.

The island consumes approximately 56,000 gallons of diesel to produce around 500,000 kWh annually, according to the Town of Gosnold annual reports (Town of Gosnold, 2000). The average cost of diesel is about \$1.40/gal, and the island's residents pay \$0.31/kWh. Fuel oil is the primary source of heat on the island with approximately 28,000 gallons consumed annually, or equivalently 860,000 kWh. The cost of heating fuel also averages \$1.40/gal, which equals around \$0.05/kWh (Town of Gosnold, 2000).

4.2 System Design Options for Cuttyhunk Island

A number of different wind/diesel system options have been studied for Cuttyhunk Island (Manwell, et al., 2001). All systems retain the existing diesels, and automation of the diesel power system is required. They also include a supervisory control and dump load sized to dissipate the maximum expected excess power. The system options vary with regards to three major design aspects: (1) size of the wind turbine, (2) degree to which a dispatchable heat storage system is used, and (3) whether all diesels can be shut-off at once. The following table summarizes these options:

TABLE 4: INPUT PARAMETERS FOR HYBRID2 MODELING

System	Rated Wind Power kW	# of Heaters	Thermal Storage kWh	Electric Storage
Simple	50	-	-	-
	100	-	-	-
	250	-	-	-
Dispatchable Heating w/ Storage	50	16	216	-
	100	16	216	-
	250	16	216	-
Diesel Shutdown Allowed	50	16	216	-
	100	16	216	-
	250	16	216	-
	50	16	216	√
	100	16	216	√
	250	16	216	√

The proposed dispatchable heating systems include the control architecture described in the previous sections of this report. The systems with thermal storage use ETS heaters with a rated power of 3.5 kW and 13.5 kWh of storage per heater. The heaters are to be distributed in homes throughout the island. Micro-controllers would serve as the distributed and central load

controllers. A wireless radio system presents the best communication option for Cuttyhunk, given the island's current communication infrastructure. Figure 5 shows a schematic of a dispatchable heater with distributed load controller inside a building. The micro-controller, radio transceiver, and relay are integrated into the distributed load control box.

Because of the difference between the price of power and the cost of heating, it would not be economical for Cuttyhunk's residents to switch from fuel oil to electric heat. Therefore, the dispatchable heating system must be billed at a lower rate compared to the primary load. This necessitates separate metering for the dispatchable heating system. Therefore, a meter must be installed between the outlet and the heater (Figure 5).

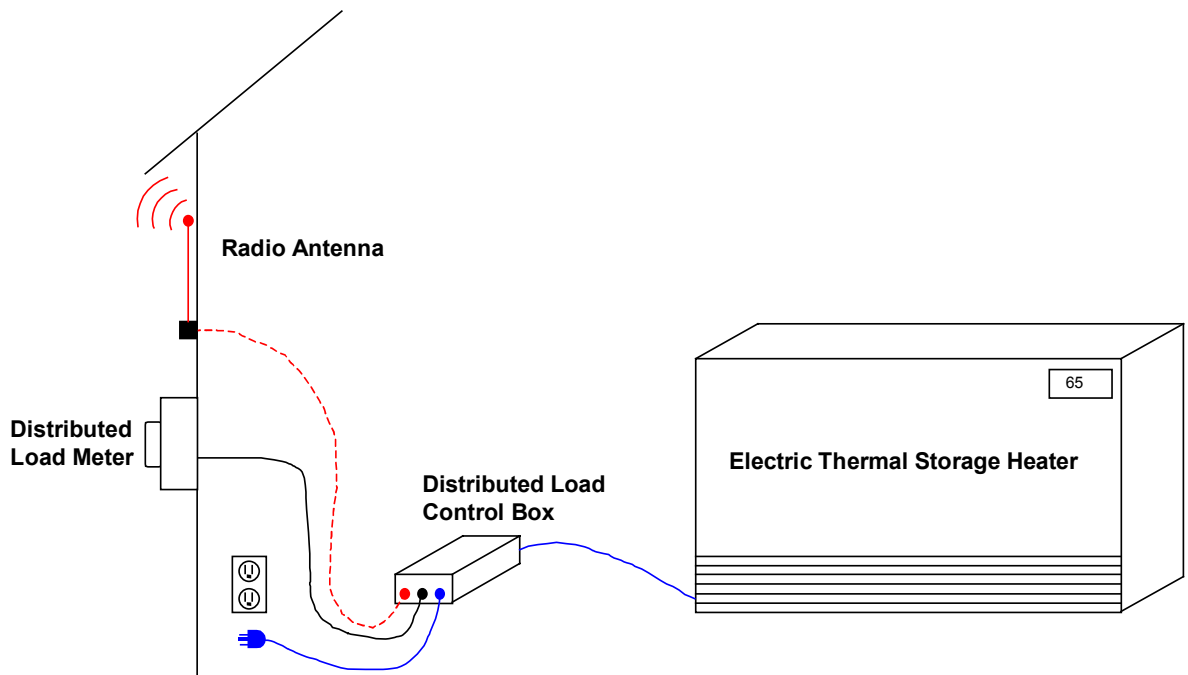


FIGURE 5: DISPATCHABLE HEAT STORAGE – END USER SCHEMATIC

For high penetration wind/diesel systems in which intermittent diesel operation is allowed, either a short-term electrical energy storage system or a synchronous condenser is proposed. The short-term storage system would include batteries or a flywheel and rotary converter or inverter. It is intended to provide about one minute of storage at the average load (60 kW). The reader is referred to Manwell, et al., 2001 for a more detailed discussion of proposed Cuttyhunk systems in which intermittent diesel operation is allowed.

4.3 Hybrid2 Modeling Results

Hybrid2 was used to model the performance and economics of the proposed wind/diesel systems over their lifetime, with the municipal utility of Cuttyhunk as the system owner. A number of conclusions can be drawn from the results. They are summarized below with regards to (1) installed wind power capacity, (2) dispatchable heating, and (3) diesel operation (Tables 5 and 6).

TABLE 5: SYSTEM PERFORMANCE FROM HYBRID2 MODELING

System	Rated Wind Power kW	Average Penetration (%)	Primary Load Served by Wind (%)	Diesel Savings (%)	Heating Load Served by Wind (%)	Useful Wind Energy (% of Total Wind)
Simple	50	40	32	24	-	77
	100	50	40	30	-	59
	250	180	58	44	-	32
Dispatchable Heating w/ Storage	50	40	32	24	6	99
	100	50	40	30	15	95
	250	180	58	44	26	54
Diesel Shutdown Allowed	50	40	34	27	5	99
	100	50	46	41	13	97
	250	180	69	65	25	60

TABLE 6: ECONOMIC RESULTS FROM HYBRID2 MODELING

System	Rated Wind Power kW	Annual Diesel Savings (\$)	Annual Heating Revenue (\$)	Payback Period (yrs)	Savings in Cost of Energy (¢/kWh)	Installed System Cost (\$/kW)
Simple	50	17,000	-	18	0	5,200
	100	22,000	-	21	0	3,800
	250	32,000	-	21	0	2,100
Dispatchable Heating w/ Storage	50	17,000	2,500	17	1	5,800
	100	22,000	6,000	17	1	4,100
	250	32,000	10,000	15	2.5	2,300
Diesel Shutdown Allowed	50	20,000	2,000	24	0	8,200
	100	29,000	5,000	19	1	5,300
	250	47,000	10,000	13	4.5	2,700

In general, the systems using either the 50 or 100 kW wind turbine did not achieve high enough wind power penetration to justify the capital costs. Although these turbines are reasonably sized to attain high penetration in the winter, they can save no more than 41% of the annual diesel consumption due to the high summer load. Because of the location, installation costs are expected to be a significant portion (~50%) of the overall turbine cost. Furthermore, the turbine installation costs on Cuttyhunk do not scale linearly with the rated power of the turbine, so that the installation costs are proportionally higher for the two smaller turbines. Systems using the 250 kW turbine can reach 50% or more in diesel fuel savings. There is also a significant amount of excess energy available for heating.

The modeling shows that the addition of dispatchable heating could significantly increase the amount of useful wind energy for all systems. Hybrid2 models the dispatchable heating system as one optional load. The rated power and the storage capacity of the optional load are set by the sum of the individual heaters. Any excess power is delivered first to the optional load. If the excess power exceeds the heating load, then the excess is put to thermal storage for the systems with ETS heaters. When the storage has reached its capacity, the excess is dissipated in the dump load. This procedure differs from the one Hertz control model discussed previously in that it does not activate the distributed heaters in discrete increments. Hybrid2 calculates the heating revenue separately from the primary load by using a different price of power for the

optional load. The price is set at 4.5¢/kWh to compete with the cost of fuel oil. The design aims to divert revenue from the fuel oil provider to the Cuttyhunk system owner. The system owner assumes the heating system costs – including installation and control hardware. The cost of the control hardware is expected to be at least 50% of the total cost of the heating system. An ETS heater costs between \$800 and \$1500, while the price of the control and communication hardware is approximately \$1200 per load control unit.

The key to an effective heating system is making the heaters dispatchable and having enough excess wind power to supply a significant portion of the heating load. The 250 kW wind turbine systems using heaters with or without thermal storage show at least a 50% increase in the amount of useful wind energy compared to systems without dispatchable heating. The added revenue translates into more savings in the equivalent cost of energy. A sensitivity analysis was performed to test the effects of using more dispatchable heaters on the system. The initial number of 16 heaters is based roughly on the number year round residents on the island. However, the total heating load is large enough to justify more heaters for the system, and the economics improve with the number of heaters. Figure 6 shows the savings in the cost of energy for four wind/diesel systems with dispatchable heating. All of the systems in the graph use the 250 kW wind turbine but do not allow for intermittent diesel operation.

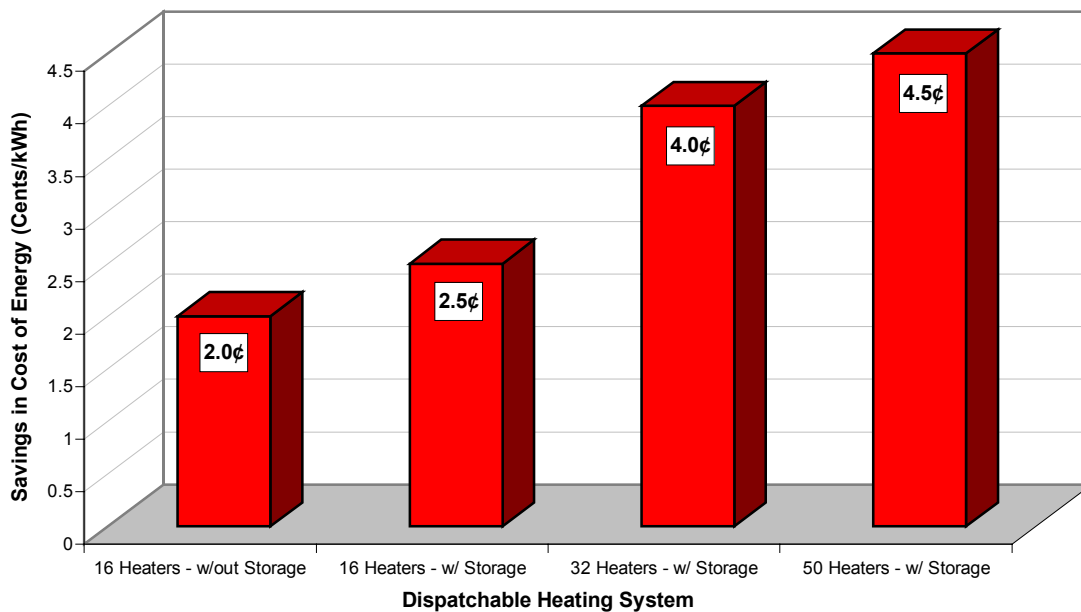


FIGURE 6: DISPATCHABLE HEATING SYSTEM COMPARISON– SAVINGS IN COST OF ENERGY FOR SYSTEMS USING A 250 KW WIND TURBINE

The high penetration systems in which all the diesels can be shut off clearly offer the greatest potential economic benefits. Due to their complexity and difficulty of modeling, the results from the systems are less concrete however. Hourly data were used to model the Cuttyhunk systems, and thus simulating short-term energy storage (on the order of a few minutes) cannot directly be achieved. Therefore, the wind variability input in Hybrid2 was reduced to model the effect of reducing the short-term fluctuations in the wind speed. This procedure may not account for all of the issues associated with short-term storage systems.

5.0 CONCLUSIONS

The purpose of the dispatchable heat storage system is to provide a solution to the seasonal mismatch between available wind power and primary load experienced by many cold climate regions. In systems with mostly distributed residential heating loads, a dispatchable heating system presents a realistic option for making use of the excess energy. The modeling done in this report shows that dispatchable heating systems could increase the economically useful wind energy and improve the wind/diesel system's feasibility.

The key to an effective dispatchable heating system is the communication and control system. The required hardware is readily available and inexpensive. The control strategy outlined in this paper offers a simple load control option. Further investigation and hardware testing are necessary to prove the adequacy of the control strategy.

6.0 ACKNOWLEDGEMENTS

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