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. The heating system’s load control strategy is 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 on Cuttyhunk Island, Massachusetts (USA).

Keywords: Wind-Diesel Systems, Load Management, Thermal Energy Storage, Cuttyhunk Island

1 INTRODUCTION

In many small-grid island communities, the summer electrical load is often significantly greater than the winter load due to larger summer populations. A typical example in the Northeastern US is Cuttyhunk Island, where the summer population reaches over one hundred while only twenty-five residents inhabit the island year-round. However, Cuttyhunk Island’s excellent wind resource does not match the trend of the electrical load; the winds are generally higher in the winter. Figure 1 shows an annual comparison between the electrical load and the wind resource on Cuttyhunk Island [1].

![Figure 1: Average monthly load and wind speed on Cuttyhunk Island](image)

This seasonal mismatch between primary electrical demand and available wind exists in many isolated cold-climate diesel systems around the world where the summer population is greater than the number of year-round inhabitants. The coastal area of New England, in the Northeastern US, has over one hundred remote power systems of various sizes that exhibit a mismatch between wind resource and electrical load [2].

In these regions, sizing the wind plant to match the load is a fundamental issue for wind-diesel system engineers. 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 turbine(s) are selected to meet the winter load, the system will be under-sized in the summer and will reach only a modest average penetration.

To make wind-diesel systems more economical in areas that experience the seasonal wind/load mismatch, designers need to find an effective long-term storage medium or end use for the excess power produced during the winter. In cold climate systems, adding secondary thermal loads is an intuitive solution, because the excess power would otherwise have to be dumped as waste heat. Numerous concepts of using excess power for heat with varying degrees of sophistication have been proposed and implemented [3,4,5]. Most of the designs involve using the waste heat from a local dump load directly for hot water or space heating to meet a large, single thermal load [6]. For such systems, these heating concepts have been able to utilize surplus wind energy.

However, in many regions the heating loads are often dispersed throughout the system in residential buildings. Utilizing these distributed heating loads as dump loads adds another level of complexity to the design. In order to maintain the system’s power balance the distributed loads must be controllable. An effective heating system also requires a load control strategy that ensures excess power is distributed equitably to the heating loads.

This paper describes the design of a dispatchable, residential heating system designed to increase the amount of economically productive wind energy in wind-diesel systems. The heating system consists of individually controllable electric space heating units with thermal storage. The paper begins with a description of the load management system and the control hardware required to realize this dispatchable heating system.

Control issues are analyzed using a 1 Hz time-series model that simulates the heating system within a 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 can 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 program to model the long-term performance of wind-diesel system options for Cuttyhunk. The results of that study are also summarized in this paper, with particular attention given to the potential economic benefits of including dispatchable heat storage in the wind-diesel system.

2 DISPATCHABLE HEAT STORAGE SYSTEM DESIGN

The concept of controllable distributed secondary loads as a method to dump excess power usefully in wind-diesel systems has existed for several years [3]. The basic idea is to add or shed the distributed loads as the excess power varies. Control is typically the main issue...
for implementing controllable distributed loads, because
the challenge is to vary the load to match the fluctuating
time.

Of the few distinct control designs for distributed
dump loads [3,5,7], the one described in this report uses
discrete remotely controlled loads. Individual electric
dispatching these loads requires a command to be
loads as the discrete loads. The central load controller
transmitted from a location in the system where the
command should switch a relay to enable or disable the
available excess power is known. In its simplest form,
command and process the command, (ii) a central controller
knowledge of the excess power to create and transmit the
The fundamental objectives of the designed heating
system are to: (1) increase the amount of economically
useful wind energy, (2) save heating fuel, and (3)
maintain quality of the primary load. Furthermore,
the control strategy restricts starting the diesel engines
to power the heating system.

2.1 Description of Electric Thermal Storage Heaters
Electric thermal storage (ETS) heating units can be
used to smooth the fluctuations in the excess power and
provide a more consistent heating power output for the
user. ETS units are resistance heaters with electric
elements encased in ceramic blocks. 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, they can provide several hours of thermal
storage, depending on the size and rated output of the
heater. Commercial units vary in rated output between 2-8
kW and in storage capacity between 10-40 kWh.

The ETS heaters are used by customers of 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 excess power is sufficiently large to supply the
necessary input power of the heater.

2.2 Dispatchable Heating Control Architecture
Figure 2 shows a two-line schematic of the control
architecture within a wind-diesel system. The heating
units are distributed in homes and buildings throughout
the system’s service area. The heating system’s control
consists of two main components: (1) central load control
and (2) distributed load control.

In order to maximize the amount of usable excess
power, the heaters are to be dispatched incrementally as
the excess power fluctuates. The smaller the rated power
of the dispatchable heaters, the better the system will be
at matching the excess power. Ideally, heating units
would be dispatched immediately whenever excess power
came available. For this heating system, 1 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, centrally located (local) dump load should
be used for that purpose.

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
the 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.

![Figure 2: Dispatchable heat storage control diagram](image)

The local dump load controller initiates the
dispatching process 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 on the wind-
diesel system. At a defined time-step (probably not
higher than 1 Hz), the central load controller broadcasts
one signal 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. The central load controller
may bundle the on/off command with a priority shifting
command and transmit the two commands as one signal.
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.

The increase or decrease of the excess power as
heaters come on or offline provides feedback to the local
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 power of the heaters in order
to dispatch the correct number of heaters.

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.

2.3 Dispatchable Heating System Hardware Components
Micro-controllers – software programmable, single
board computers – can be used for both the central and
distributed load controllers (see Figure 2). Each load
controller would have one micro-controller to process
incoming data and execute commands. The protocol used
by the micro-controllers is flexible.

Wireless radio offers a simple and robust option for
the communication system. Radio frequency transceivers
(modems) can transmit and receive digital signals over
several miles. 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. Each transceiver uses an antenna to broadcast or receive signals.

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

3 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 intends to analyze a proposed wind-diesel system on Cuttyhunk Island. 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 integrates a dispatchable heating system with a simple wind-diesel system. The input parameters for the wind-diesel portion of the model include characteristics of the wind turbine(s) and diesel generator(s). Using these parameters and time series data of wind speed, primary electrical load and outdoor temperature the model calculates wind power, excess power and heating load. The inputs for the heating system consist of distributed heater attributes and the control algorithm outlined above.

The primary load is first met by wind power. Any shortfall is covered by the diesels. High frequency fluctuations in the excess power – the sum of the diesel and wind power minus the primary load – are dissipated through the local dump load. Dumped power above a safety minimum is farmed out to the distributed heaters based on their priority levels. When there is no heat load or the heat storage is full, the local dump load absorbs the excess power.

All simulations use one complete day of 1 Hz time series data. Two different data sets were used to represent a winter day and a day in the fall or spring on Cuttyhunk Island. All data sets were synthesized using the autoregressive moving averages technique with hourly mean values taken from real data on Cuttyhunk [8].

The results from all simulations indicate that equal distribution of the excess power is readily achievable if the following condition is met: the load priority levels must be shifted often enough to rotate the priorities through one complete cycle over the desired time period.

Three main factors influenced the amount of excess power utilized for heating: (1) wind turbine rated power, (2) heater quantity and rating, and (3) the rate at which heater on/off commands are issued. In general, the amount of available excess power varied significantly with the size of the wind turbine. The useful wind energy increases with the number of heaters and their rated power and storage capacity. The magnitude of the increase is naturally limited by the rated 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 results indicate that increasing the time period between the on/off switching commands reduces the amount of usable excess energy.

The time-varying heating demand limits how much excess power can be utilized for heat. The model assumes that the equivalent heat load of each heater fluctuates continuously with the outdoor ambient temperature. In reality, heating systems might 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 LONG-TERM PERFORMANCE MODELING ON CUTTYHUNK ISLAND

The wind-diesel system modeling program, Hybrid2, has been modified to simulate heating loads with thermal storage [9]. This version will soon be available from the National Renewable Energy Laboratory (NREL) in Boulder, CO (USA). It is used 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 a small island situated about 23 km off the southern coast Massachusetts. One year of hourly wind speed, electrical load, and temperature data from a previous study on Cuttyhunk were used for the modeling described in this paper [1]. The average wind speed through the winter on Cuttyhunk is 8.9 m/s, while the summer has a mean wind speed of 6.3 m/s. The annual average of the primary load is 60 kW, but the hourly load peaks near 300 kW in the summer.

The island consumes approximately 56,000 gallons of diesel to produce around 500,000 kWh annually [10]. Fuel oil is the primary source of heat on the island with approximately 28,000 gallons consumed annually, or equivalently 860,000 kWh. The average cost of diesel and fuel oil is about $1.40/gal, and the island’s residents pay $0.31/kWh of electricity.

4.2 System Design Options and Hybrid2 Modeling

A number of different wind-diesel system options have been studied for Cuttyhunk Island [8]. All system options retain the existing diesel power system. They also include a supervisory control and a local dump load sized to dissipate the maximum expected excess power. For the purpose of this paper, discussion is focused on two major design aspects: (1) wind turbine rated power and (2) degree to which dispatchable heating system is used.

Systems were modeled using a 50 kW, 100 kW or 250 kW wind turbine. Three options were proposed with regards to the heating system: (1) no heating system, (2) dispatchable heating without thermal storage, and (3) dispatchable heating with thermal storage. The proposed dispatchable heating systems include the control architecture described in the previous sections of this report. Systems with thermal storage use ETS heaters with a rated power of 3.5 kW and 13.5 kW of storage per heater. The heaters are intended to supplement the island’s existing domestic heating system.

The economics were modeled with the municipal utility of Cuttyhunk as the system owner. Because of the
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 management option. Further investigation and hardware testing are necessary to prove the adequacy of the control strategy.

5 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