Hybrid Renewable Energy System Analysis for Off-Grid Great Lakes Residential Housing

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Abstract

Renewable energy has become an important area of research and development for both environmental as well as economic reasons. At the academic level, it is possible to introduce students to issues related to renewable energy. This paper discusses the effort two students put in, as part of a thesis, and an independent study, to develop an economically feasible, self-sufficient, renewable energy system for a residential home in the Great Lakes region. The design of the system sought to use both wind and solar energy to supply energy to the home. The students were able to consider effects such as the design and capability of the wind turbine and solar panels to determine whether the design would be viable economically. After deciding that the initial system design would be too expensive, the students then considered other options to reduce the cost of the renewable energy system while still providing the necessary electrical systems that are used in a modern home. This included the development of a survey that was distributed to faculty and staff. The survey was used to determine the critical electrical loads that families in the Great Lakes region would require throughout the year. From this data, the average daily, weekly, and annual power requirements for a 2,000 square foot home was determined. Hybrid energy systems (using wind and solar power only) were then researched and priced to determine feasibility in the Great Lakes region. Alternative and supplementary sources of home and water heating were also explored in an attempt to reduce energy consumption in order to meet the specified cost requirements of the renewable energy project. Successes and challenges of developing a completely self-sufficient (off of the commercial electrical grid) home in the Great Lakes region of North America using renewable energy will be discussed.

Introduction

The purpose of this project is to consider the feasibility of developing a hybrid renewable energy system that is capable of providing enough electrical power to sustain a family of 4, in a 2,000 square foot, 8 room home in Northwestern Pennsylvania (Erie, Pa.). The system was originally proposed to meet the following criteria:

- The system must operate completely off of the commercial power grid.
- The total hybrid system cost must not exceed $10,000.
- The system must be able to convert enough solar and wind energy to usable energy to sustain a 2,000ft^2 home in the Great Lakes regional climate.
- The system must provide a means of energy storage in order to maintain power during periods of low solar and wind activity.

It was determined in an earlier study done at Penn State Erie, The Behrend College that it was not possible to produce this system if all of the common electrical household items found in an average home were to be used [1]. In order to make the project more feasible, the electrical devices to be used in the home was limited to the 10 most critical loads for a home in this climate. To determine the critical loads, a survey was conducted among the faculty and staff at Penn State Erie, The Behrend College [1]. The 10 loads that were chosen are shown below:

- Refrigerator
- Electric Clock-Radio
- Vacuum Cleaner
- Clothes Washing Machine
- Electric Clothes Dryer
- Inside Household Lighting
- Electric Household Heating
- Electric Water Heater
- Personal Computer with Printer
- Electric Range/Oven

It was also determined in the same study that the lack of average daily sunlight generated during the winter months in the Great Lakes region was adequately supplemented by the increase in average daily wind velocity during the same period [1]. Information obtained from the National Oceanic and Atmospheric Administration on wind and solar activity in Cleveland, Ohio over a five-year period (September 1996 through September 2001) was used to calculate the approximate daily energy that could be generated from both wind and solar energy in the region. Figures 1, 2, and 3 show the results obtained for solar, wind, and both solar and wind respectively.

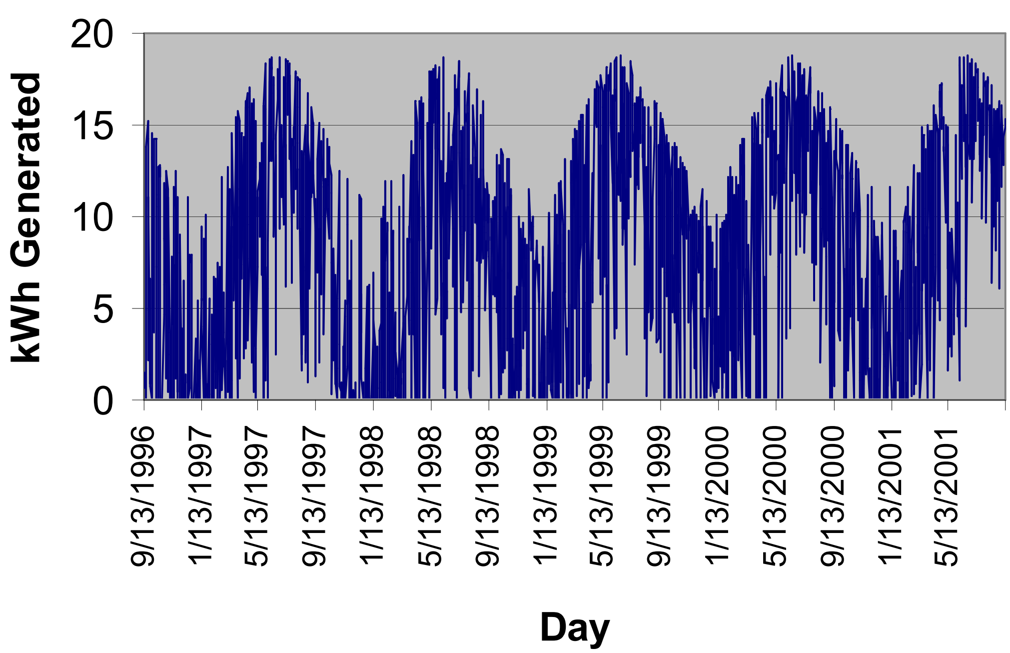

Figure 1: Calculated daily energy generated from a solar panel in the Great Lakes region.

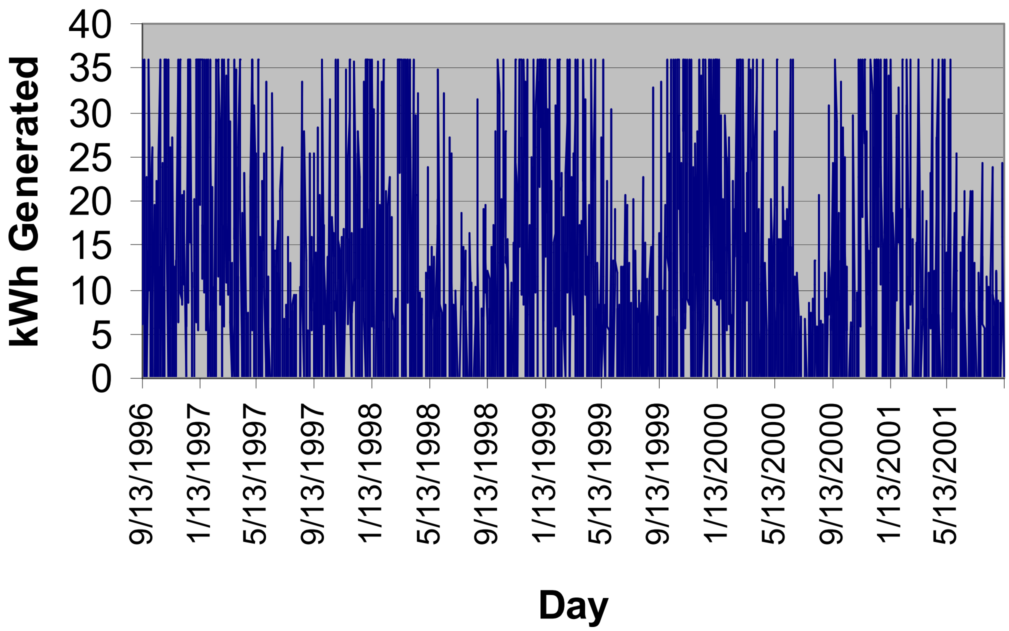

Figure 2: Calculated daily energy generated from a 1.5kW wind turbine in the Great Lakes region.

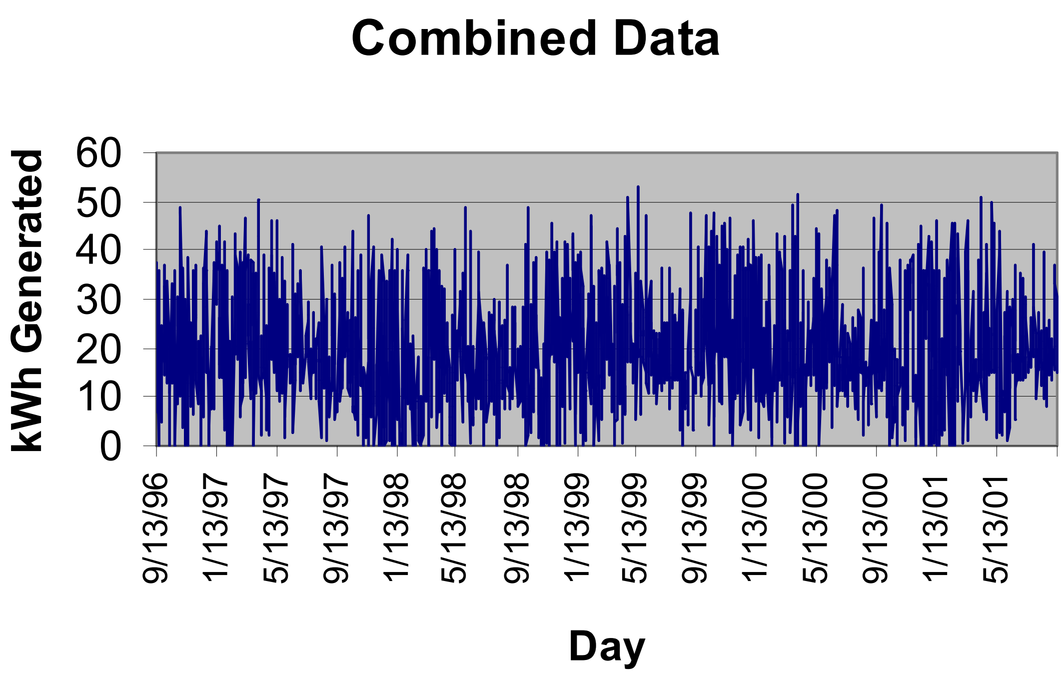

Figure 3: Calculated daily energy generated from a 1.5kW wind turbine and a solar panel combined in the Great Lakes region.

These results confirm the theory used in the previous report that the average wind and solar energy generated in this region during the winter and summer months are indeed complimentary to each other [1]. Based on these conditions, a model home will be designed using the power delivery capability of the hybrid system, and the power consumption of the 10 critical loads as the main elements of the model. Once the feasibility of the model home has been considered, a 1/10-scale model will be constructed to simulate the actual conditions and test the theory of the project recommendations in a smaller scale.

Specification Requirements

Using the average power consumed by the 10 critical loads determined in the previous study, a daily, weekly, and annual power consumption for the model home was determined (see Table 1). A total of 18 various references were used for the calculations (see Table 3), and any reference that deviated more than 50% from the median was not used for the calculation of the averages shown in Table 1.

Table 1: Estimated average power consumption (in kilowatt hours) for a 2000ft^2 home in the Great Lakes region.

Time Period	**Daily Avg.**	**Weekly Avg.**	**Annual Avg.**
Power Consumed	78.02kWh	545.94kWh	28471.91kWh

From these estimations it is shown that the annual power generated from the hybrid system would need to be approximately 28,500kWh in order to sustain a 2,000ft^2 home in the climatic conditions of the Great Lakes region. In order to have power available during times of low sunlight and wind, a battery bank capable of storing the amount of energy needed must be included in the system. The battery bank must be charged by the solar panel and wind turbine whenever enough sunlight and/or wind is available, therefore both must be sized accordingly to restore the energy used by the various loads to the battery bank. Four of the electric home heating references from Table 3 were used [12, 13, 15, 20] to calculate the peak power that would be used at any given time in the model home. Electric home heating is the most critical factor for peak power consumption because heating in winter consumes the most energy by far than any of the other critical loads in the model home. In addition to the home heating peak consumption, an additional 1.5kW was added to the result of the calculations to account for other loads that may be operating at the same time as the heater. Table 2 below shows the results of the calculations:

Table 2: Peak Power Consumption (Home Heating Plus 1.5kW).

Reference	**Heating 6 of 8 Rooms**	**Heating All 8 Rooms**
www.eere.energy.gov [12]	8.25kW	10.50kW
www.ntpc.com [13]	7.5kW	9.50kW
www.macgen.com [15]	13.5kW	17.5kW
Moncrief Corp [20]	13.87kW	17.99kW
Average (all 4 sources)	**10.78kW**	**13.87kW**
Average (internet only)	**9.75kW**	**12.50kW**

Based on the results of the calculations, it was determined that the battery bank and wind turbine together must be able to deliver a peak power of between 10kW and 14kW minimum. The solar panel is not required to deliver as much peak power as the wind turbine because the peak power draw will occur in the winter months when the battery bank will be much more dependant on the wind turbine for recharging than the solar panel. The battery bank voltage can range from 12Vdc to 240Vdc depending on the system chosen. The dc voltage from the battery bank must be converted to a useable 120Vac sinusoidal waveform through the use of a power inverter system. The power inverter itself consumes power, so approximately 20% of the dc power will be lost converting to useable ac power. Taking these factors into consideration, it was determined that the battery bank and wind turbine together must deliver a minimum of 12.5kW peak. From the data collected in Table 1, and the 20% power inversion loss expected, it was determined that the battery bank must deliver a constant average power of 3981.13W. Therefore the battery bank must be rated at a total power capacity of 16.59Ah for a 240Vdc bank, 33.18Ah for a 120Vdc bank, up to 331.76Ah for a 12Vdc bank, in order to store enough energy to deliver the constant average power of 3981.13W.

Design Features

The proposed hybrid system using solar and wind power that would be used to power the model home would consist of the following components:

- A 10 to 15 kilowatt wind turbine and associated wiring components.
- A 60 to 100 foot support tower for the wind turbine.
- A wiring kit for the wind turbine support tower.
- A 0.65 kilowatt solar panel and associated mounting and wiring materials.
- A dc power center for system component integration (includes rectifiers & fuses).
- A 100 kilowatt-hour battery bank and associated wiring components.
- A 10 to 15 kilowatt sine wave or modified sine wave inverter.
- Various battery charging and voltage regulating components

A block diagram of the proposed hybrid system showing the component connections and configurations is shown in Figure 4:

Design Issues

The two biggest problems to overcome in the design of the hybrid system are the amount of electrical power required to heat water and living space in the model home (see Table 3). The average annual power consumption drops from 27454.28kWh to 2900.93kWh when the electric water heater and home heating are removed from the power consumption calculations. Figure 5 shows a comparison of the power consumed by the 10 critical loads.

From this comparison it is clear that household heating is by far the largest power consumer, which accounts for 74.5% of the annual power consumed. Heating water is the second biggest consumer of power at 18.6% of the annual power consumed. Because of the large percentage of total power consumed by these two loads (93.1%) the decision was made to re-evaluate ways of heating water and home living space. Due to claims of higher heating efficiency for heating water, a tank-less water heater was considered. Water flow rates were measured at a local household, and average water usage for a family of 4 was estimated. After some heat transfer and physics calculations, it was determined that the tank-less water heater would consume 4965.12kWh annually. This determination was not much different than the original estimation for a hot water heating tank of 5116.17kWh (2.9% reduction). It was concluded from this data that although a tank-less water heater was more efficient, it did not constitute a big enough difference to have any impact on the overall power consumption problem. For the most substantial problem of home heating, alternative methods of heating were explored. A ground source heat pump system was evaluated, but found to be impractical in this climate. Through researching the U.S. Department of Energy website, and a telephone conversation with Moore Heating (local heat pump sales and service) in July of 2004, it was determined that the initial cost of installing the heat pump would be at least $10,000, and due to the lack of latent heat in the ground during the winter months, the piping for the system would need to be more than 200 feet deep making installation and maintenance impractical for this application [2,3].

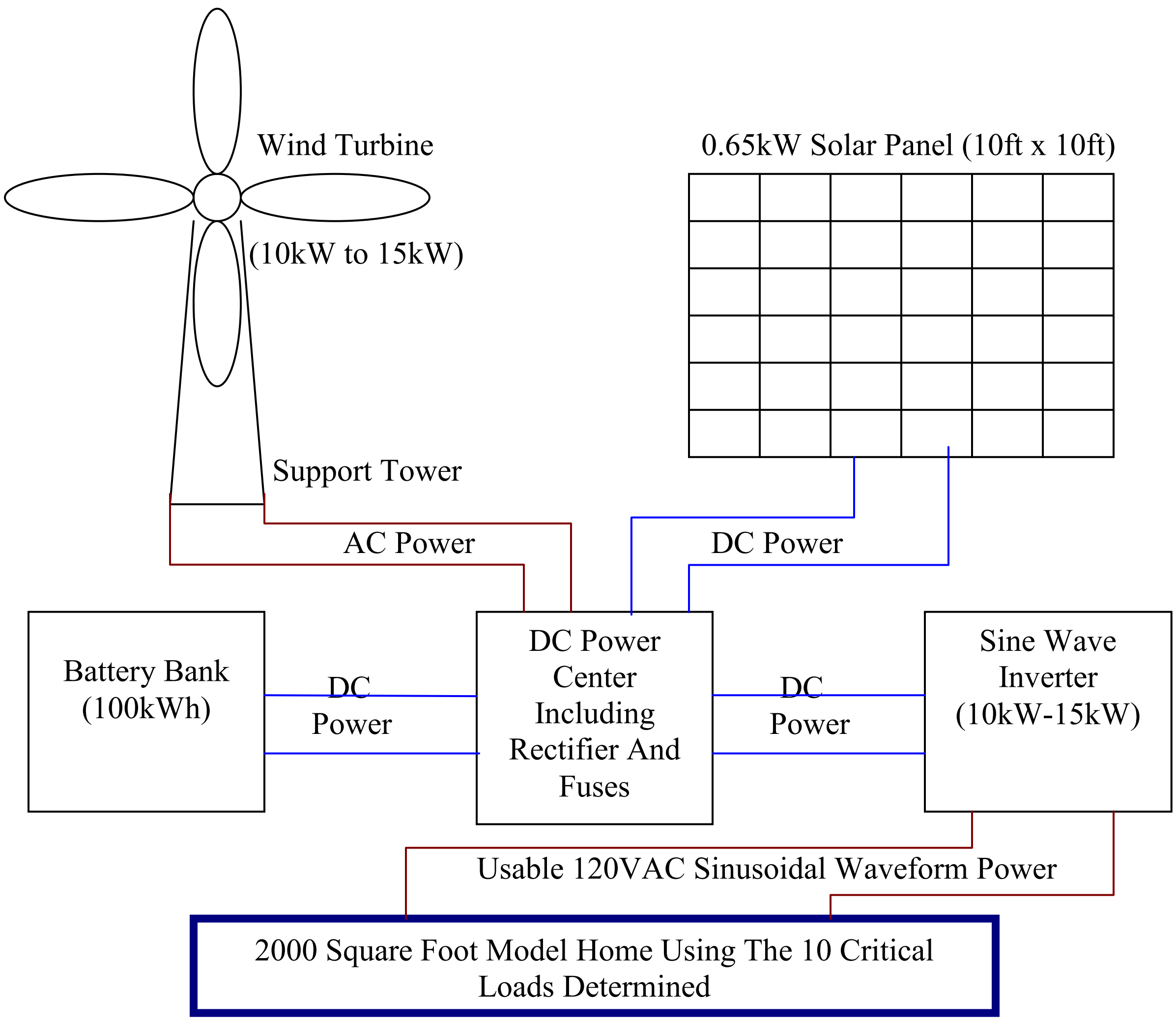

Figure 4: Block diagram of hybrid power system.

Table 3: Critical load data.

Critical Load	Daily Avg. kWh	Weekly Avg. kWh	Annual Avg. kWh	References Used
Refrigerator	1.45	10.13	528.21	[1,8,9,13,15]
Vacuum Cleaner	0.23	1.59	82.68	[8,9,10,12,16,17,18]
Electric Clothes Dryer	2.08	14.47	759.66	[8,9,12,13,14,15,16,19]
Electric Home Heating	56.04	392.28	20454.81	[12,13,15,16,20,21]
Electric Range/Oven	2.80	19.57	1020.43	[8,9,12,13,14,16,]
Clock-Radio	0.11	0.76	39.38	[10,11]
Clothes Washing Machine	0.30	2.08	108.52	[9,12,13,16]
Interior Home Lighting	0.61	4.25	221.74	[8,9,15]
Electric Water Heater	14.02	98.12	5116.17	[13,15,22a,22b]
Laptop_Computer/Printer	0.38	2.69	140.31	[1,13]

Note: Reference 22a = Electric Heater, 22b = Gas Heater (energy conversion to electric)

GRAND TOTALS WITHOUT ELECTRIC HOME HEAT AND WATER HEATER:

DAILY AVERAGE = 7.96kWh, WEEKLY AVERAGE = 55.54kWh

ANNUAL AVERAGE = 2900.93kWh

GRAND TOTALS INCLUDING ALL 10 CRITICAL LOADS:

DAILY AVERAGE = 78.02kWh, WEEKLY AVERAGE = 545.94kWh

ANNUAL AVERAGE = 28471.91kWh

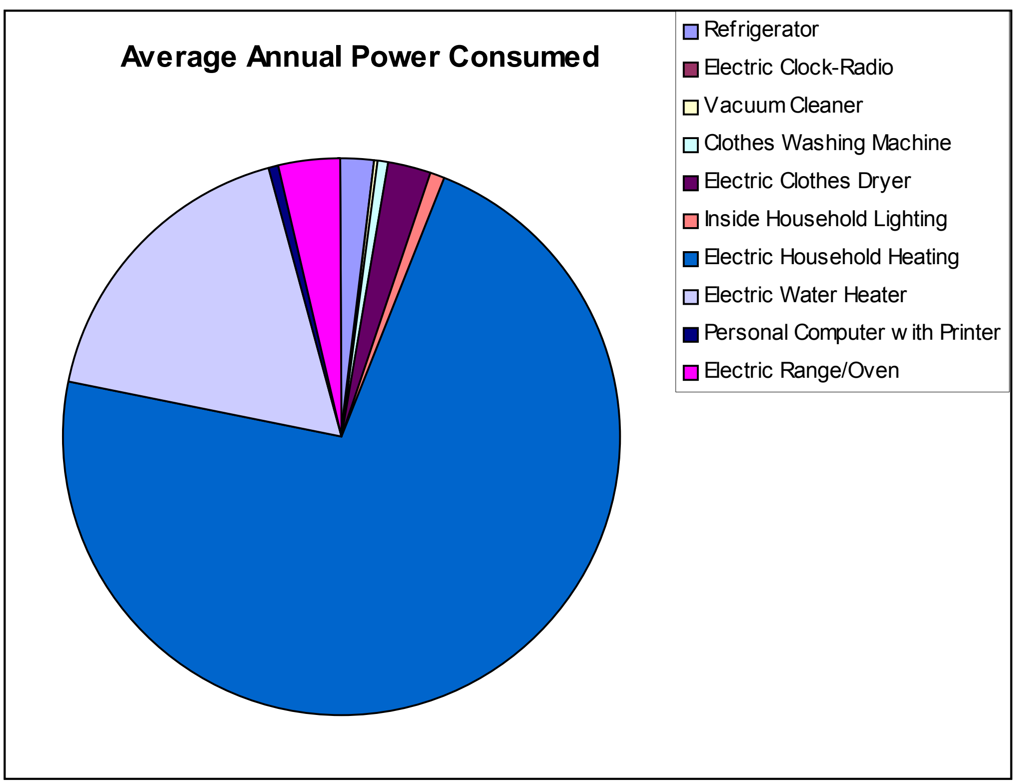

Figure 5: Average annual power consumed by the 10 critical loads

Critical Load Details
Table 3 lists all of the references and power consumption data used to calculate the average power consumed by each critical load, and the total power consumption (with and without the living space heater and water heater). All of the data recorded was based on a family of 4 living in an 8 room, 2,000ft^2 home. Data obtained for the refrigerator was either taken directly from the source, or converted from power data obtained from the source by estimating that the compressor for the freezer runs 6.5hours/day, and the compressor for the refrigerator runs 2.8hours/day. The vacuum cleaner data was converted from source power consumption information, estimating an average usage of 1.5hours/week. The electric clothes dryer power consumption information was converted from the source at an estimated 3.5hours/week average usage.

Two of the home heating source references in Table 3 used specified power consumption information from the manual and were converted by using either direct electrical power information [20], or by doing a BTU to kWh conversion from a gas furnace [21]. The other remaining electric home heating sources in Table 3 [12, 13, 15, 16] were single room heaters. The total power consumed by the single room heaters (for the entire household) was calculated by estimating 8 separate room heaters, each of which were estimated to be on for an average of 4.8 hours/day over the course of an entire year. The average number of hours per day of 4.8 was arrived at by estimating that in the coldest 2 months of the year the daily average heater duty cycle is 60%, the next 2 coldest months the daily average heater duty cycle is 40%, and in the 2 least cold months of year the daily heater duty cycle is 20%. For the 6 months of the year that the home heating is on, the average duty cycle is 40%, however that only accounts for half of the year so the annual average daily duty cycle is 40% * (1 / 2) = 20%. Then 20% of 24 hours is calculated to be the daily average over the course of a year, which is equal to 4.8 hours/day that the home heating unit is operating on average.

The electric range/oven power consumption totals were calculated from the source data by estimating an average daily usage of 2 hours for the range burners plus 0.5 hours for the oven. Clock-Radio power consumption data was either converted directly from the source [8, 9, 12, 16], or converted estimating a 10W radio at half volume (approximately 0.1mW) for 5 hours/day while the clock runs constantly [10, 11]. (Note: references [8, 9, 12, 16] were not used in the average power consumption calculations due to a more than 50% deviation from the median power consumption value). The clothes washing machine power consumption data was calculated from the source data by estimating an average of 4.5hours/week usage. The inside lighting was calculated from the source power consumption data with an estimation of 10 – 20W compact fluorescent bulbs. The average power consumed per day was calculated for 4 – 20W bulbs not on at all, 1 – 20W bulb on for 8 hours/day, 2 – 20W bulbs on for 6 hours/day, 1 – 20W bulb on for 4 hours/day, and 2 – 20W bulbs on for 2 hours/day on average. The total on time per day was then calculated to be 28 hours average for all 10 bulbs, or 2.8 hours/day/bulb on average.

The electric water heater power consumption data in Table 3 was calculated by estimating the average daily on time to be 6 hours, and then either converting direct electrical power specifications [12, 13, 15, 16, 22a], or converting BTUs to kWh using a gas operated water heater [22b]. A follow up study on European style tank-less electric water heaters revealed only a 2.9% reduction in annual power consumption by converting from hot water tank style heaters. This was deemed to be too slight of a difference to be concerned with; therefore the original data was used in the overall calculations. The laptop computer and printer data was obtained through direct measurement from the source [1], or converted directly from source power consumption data [13].

Conclusion

Based upon the data gathered in the last two reports done on the feasibility of operating a 2,000 square foot, 8 room home for a family of four, that could operate completely off of the commercial power grid in the Great Lakes region, a minimum of $50,000 would be required to make the conversion [4, 5, 6, 7]. This figure is 5 times greater than the target conversion cost of $10,000. The cost in material alone for a 10kW wind turbine system, excluding the solar panel and mounting/wiring materials for the solar panel, is approximately $40,000 [4]. A 10.1kW hybrid system using a 7.5kW wind turbine, 100-foot tower, 2.6kW solar panel, 84kWh battery bank, 11kW inverter system, and all other accessories necessary for operation, costs $67,370 uninstalled [4]. Installed, the system would easily exceed $75,000. With the costs of the hybrid system ranging from 5 to 10 times greater than the target price, alternative ways to lower costs must be explored. The number one priority in reducing power consumption, thus reducing overall costs, is to find alternative methods of electric home heating. Since heat pumps are costly to install and will not generate enough heat in this climate without having to go unreasonably deep into the Earth for enough latent heat, they are not practical for primary home heating in the Great Lakes Region of the U.S. If heat pump installation costs come down, or can be reduced in some manner, perhaps a ground source heat pump system could be used in conjunction with electric heat to bring down overall electrical power consumption. The second biggest electrical power consumer of the 10 critical loads is by far the water heater; therefore alternative methods of heating water also should be further explored. With home and water electric heat accounting for 93.1% of the average annual power consumption of the 10 critical loads, it becomes obvious that this is one of the main areas of concern in order to make this project feasible in the future. Improvement of solar panel, wind turbine, and power storage technology will also help bring the price per kWh generated down, which will help to reduce hybrid-system component costs in the future.

References

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[22b] State Industries, Incorporated, model PR6 40 NBRT971 natural gas water heater.

Biographies

ROBERT S. WEISSBACH received his Ph.D. in electrical engineering from Arizona State University. He is an associate professor of engineering at Penn State Erie, the Behrend College, where he is currently the program chair in Electrical Engineering Technology. His research focuses on power electronics, power systems and multidisciplinary education.

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