CHAPTER SEVEN

HYBRID SYSTEMS SIMULATIONS

When the wind is in the east,
'tis good for neither man nor beast.

| old English proverb

In UW-Hybrid, an AC/DC bus links diesels, wind turbines, PV modules, a battery bank, and a power converter. UW-Hybrid utilizes time series weather files, which can be Typical Meteorological Year data, parametrically generated synthesized data, or external data files. Loads data are read as time series data.

In this section, the operation of the UW-Hybrid simulation program and its newly developed components is presented. The operation of each of the new components is first verified, then validated. UW-Hybrid is then exercised in a modeling case study. The results of the modeling case study are examined and reported.

7.1 Verification of UW-Hybrid Operation

The first step in determining the validity of the performance of a simulator is the verification of the operation of its components. The performance of each of the individual components can then be reviewed in order to diagnose potential problem areas. When each of the components demonstrates representative operating behavior, then the overall model is more likely to perform properly as well.

The operation of each of the newly developed components in UW-Hybrid was verified by exercising the component using a demonstration simulation (TRNSYS /TRNSED decks) designed for the verification. The performance of each component, as directed by the demonstration deck, was then examined. The results for each of the new components are presented below.

7.1.1 *Wind Turbine*

A TRNSYS deck with wind speed set to equal time was used to verify the wind turbine performance model. The performance of the wind turbine was observed as wind speed increased. The observed output of energy per time step, turbine hours, and coefficient of performance where displayed on the on-line plotter. This process was repeated across a range of atmospheric (air density, shear exponent) conditions and power regulation control modes (stall-regulated, power regulated). The results were output to a data file which was examined for correlation with the turbine power curve. Typical results are presented in figure 7.1 The results indicate that the wind turbine component accurately modeled the operation of the wind turbine. Typical results are given in Figure 7.1.

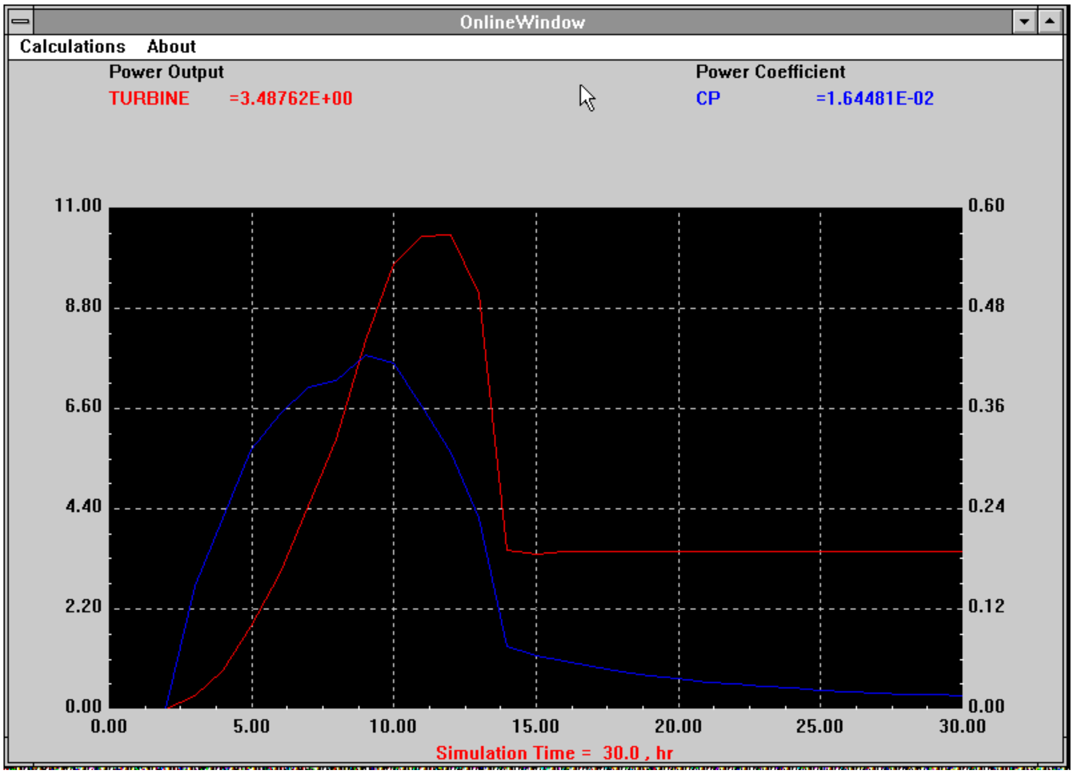

Figure 7.1 Typical plot from the wind turbine verification simulation.

7.1.2 *Wind Turbine Cluster*

The operation of a wind turbine cluster component was verified by modeling a prescribed set of conditions and examining the output. These conditions were:

Four turbines in a linear plan form.

Four turbines in a symmetric cubic plan form.

The outputs from each of the simulations was inspected to ascertain whether the coordinate transformations and wake superpositions were correctly applied. The power output of each turbine was then examined to assess its behavior over varying wind speeds and directions. Finally, output from the turbines was compared with the Type 85 model output, to check for similarity under the condition of no wake effects.

The results of the verification produced plots of output as a function of direction. Figures 7.2 and 7.3 show the cluster total output for the in-line plan and the symmetric plan. The results of the in-line simulation confirm that the coordinate transformations are correctly applied.

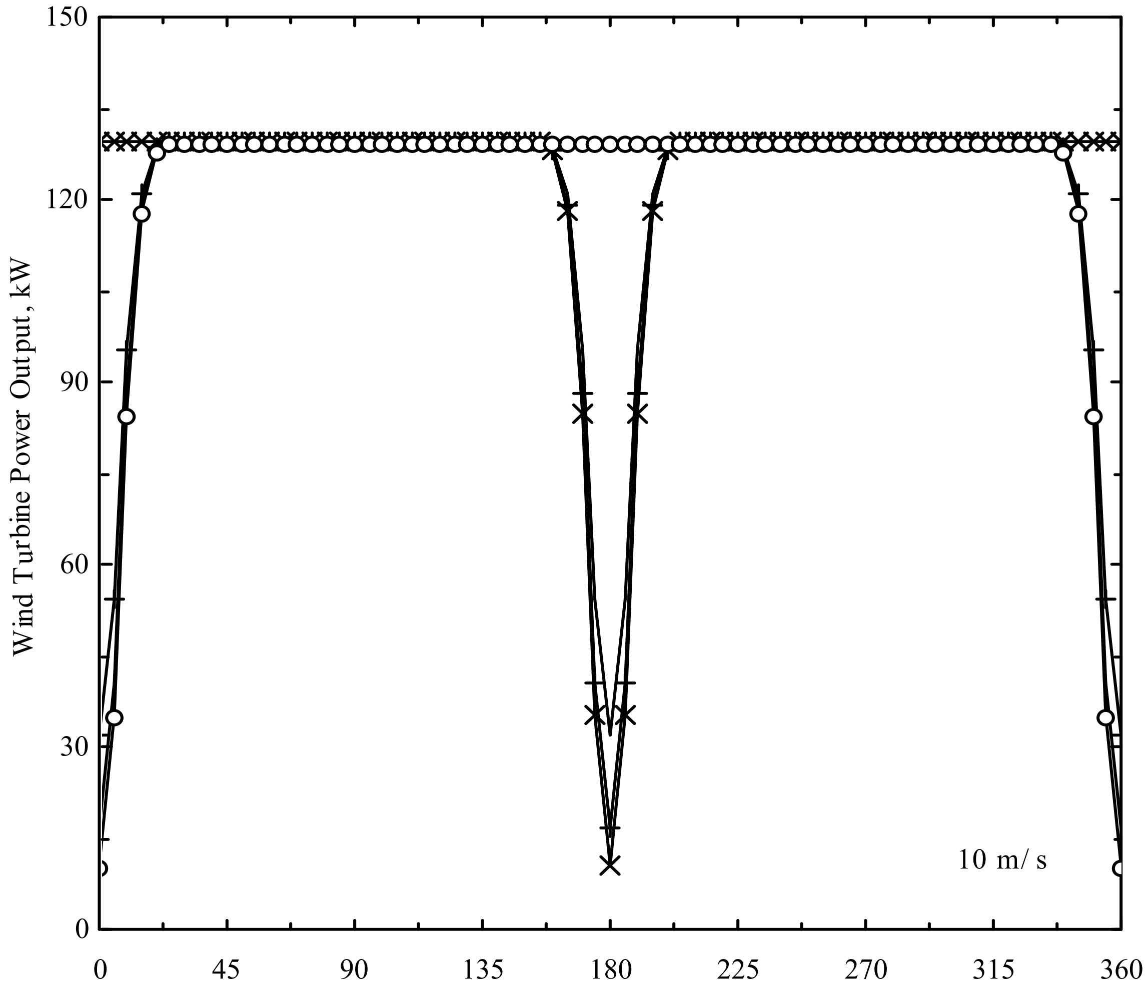

Figure 7.2 Cluster output as a function of wind direction, for an in-line site plan.

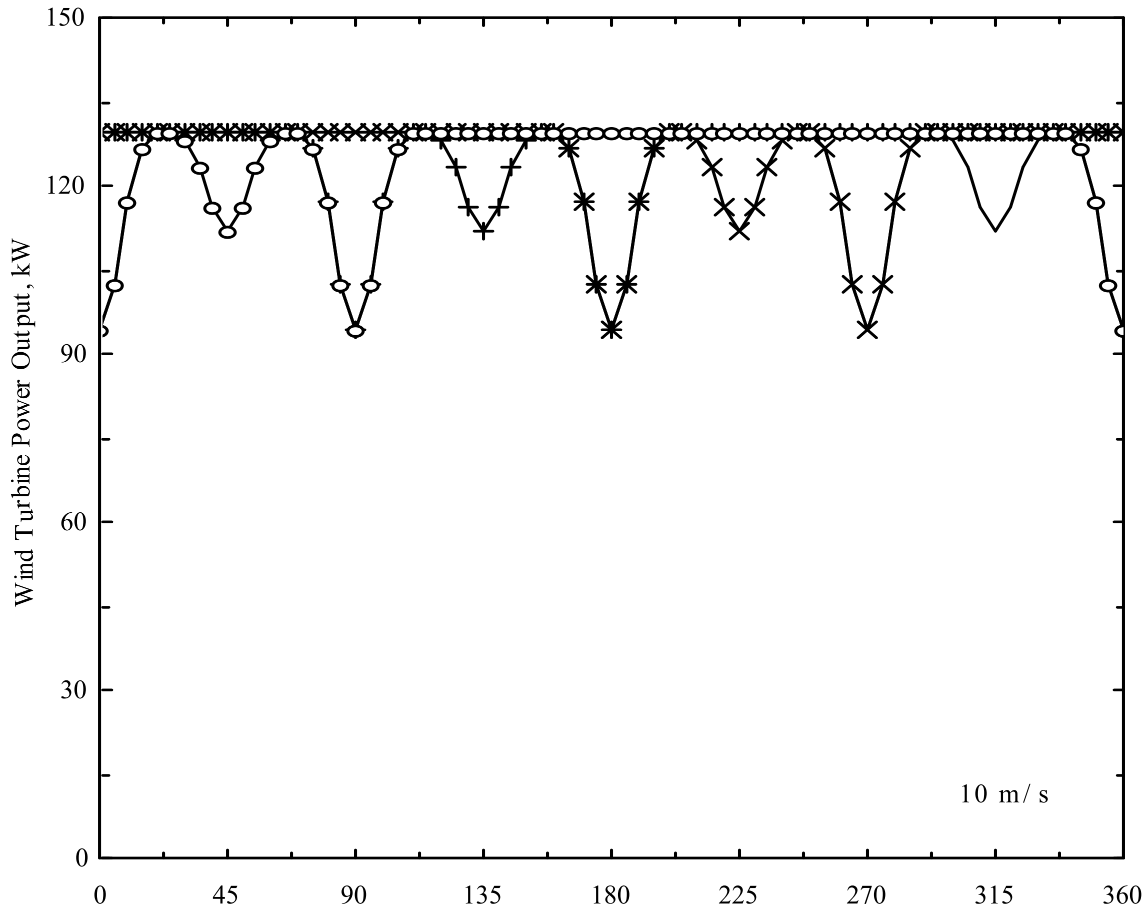

Figure 7.3 Cluster output as a function of wind direction, for a symmetric site plan.

7.1.3 *Diesel Engine*

The diesel engine, Type 90, was verified using a TRNSED simulation. Figure 7.4 shows the output from an example run. Output, waste heat and fuel usage were plotted and examined. The TRNSYS on-line plotter used to create the figure was configured to create a plot size about ten percent bigger than the maximum rating of the diesel.

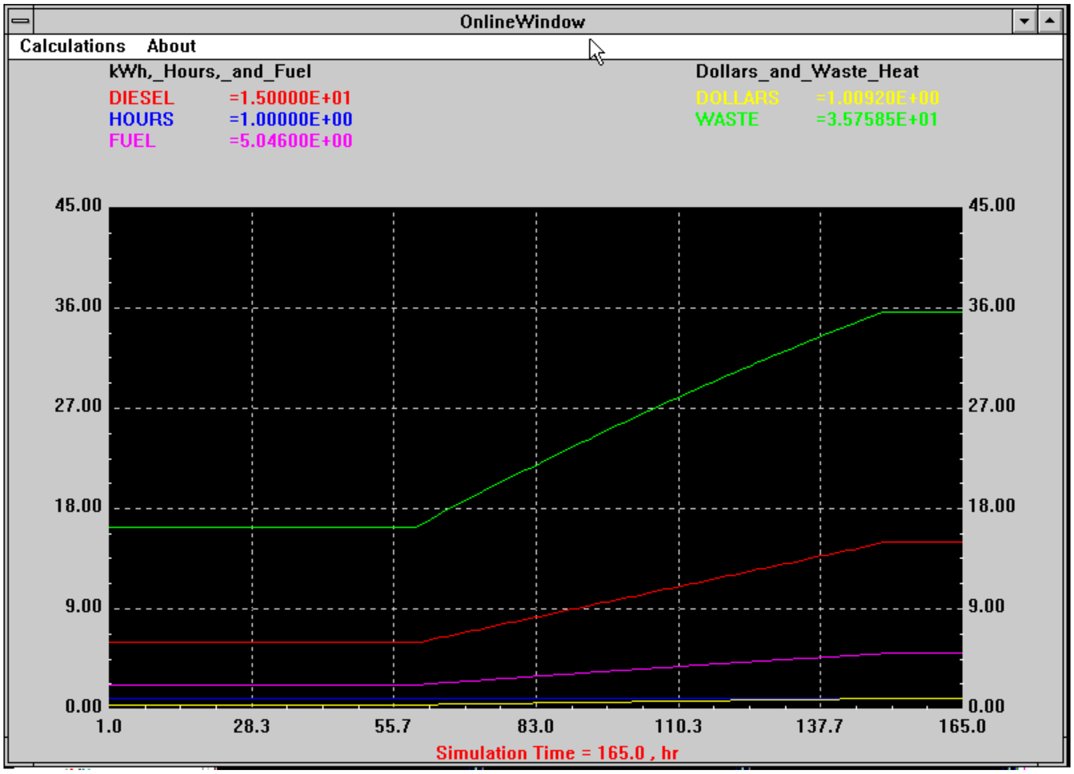

Figure 7.4 Diesel output showing diesel output and waste heat as a function of load.

7.1.4 *Diesel Dispatcher*

The diesel dispatcher, Type 92, was verified by simulating a range of scenarios, including random order, identical units, zero, one, two, three, four or five units. When the dispatcher was given identical units, it chose the first as the lower fuel-use generator. Figure 7.5 depicts the output from a demonstration run of five different diesel generators. The output is comparable to the results shown in Figure 4.7, but for a different combination of generators. The figure shows how the dispatcher reduces the apparent demand on the diesels in a prioritized order.

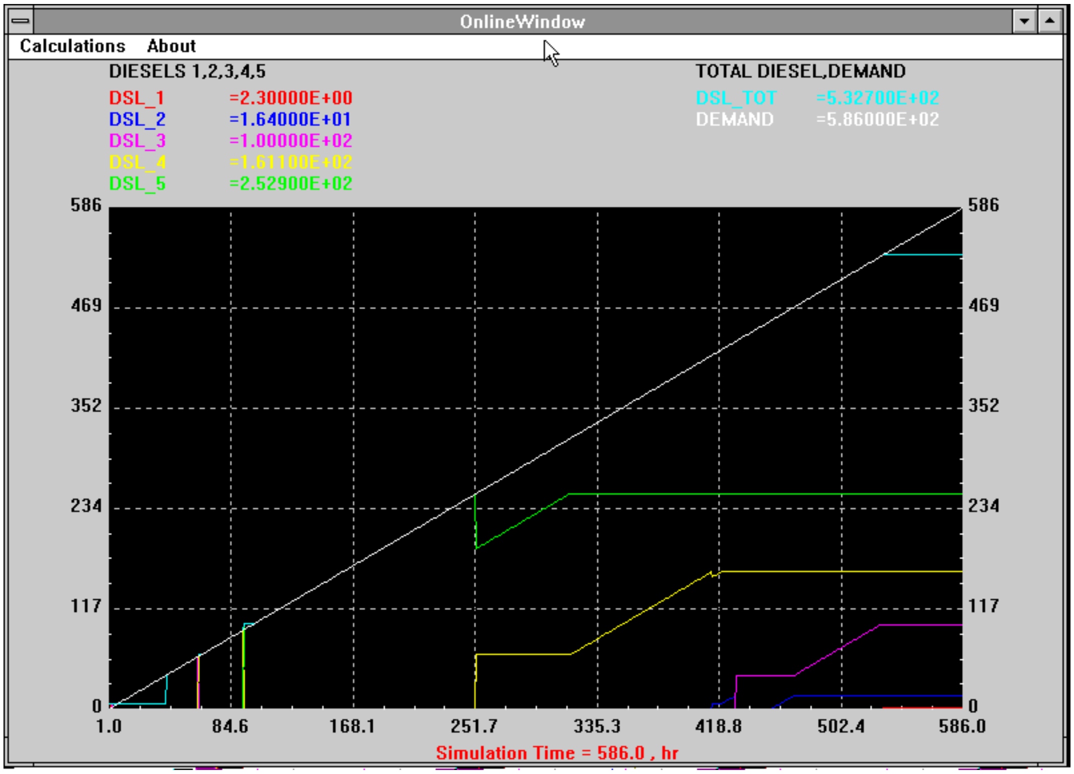

Figure 7.5 Typical diesel dispatch for five units.

7.1.5 *Power Converter*

The operation of the power converter was verified by setting demand equal to time. Figure 7.6 shows the output of the power converter, including input power, demand, wasted power and unmet demand.

7.1.6 *Storage Battery*

The storage battery component was verified in a manner similar to the inverter. The current applied to the battery was varied from negative to positive for a suite of charge states. Figure 7.7 shows a screen from the battery simulation, with state-of-charge and voltage highlighted.

After all of its components had been verified, the operation of the UW-Hybrid was verified. This was performed by examining its operation over the course of a time series of input data. Several particular locations were extracted for detailed examination. Figure 7.8 depicts the operation of the model for a week of TMY data. The data used to produce Figure 7.8 were obtained from the `UW-HYBRID.OUT` output data file. Note the reduced diesel output when renewables output increases. Also note the diesel dispatching and maximum diesel output at time = 4373. The on-line plot of the simulation week from which this data was prepared is shown in Figure 6.6.

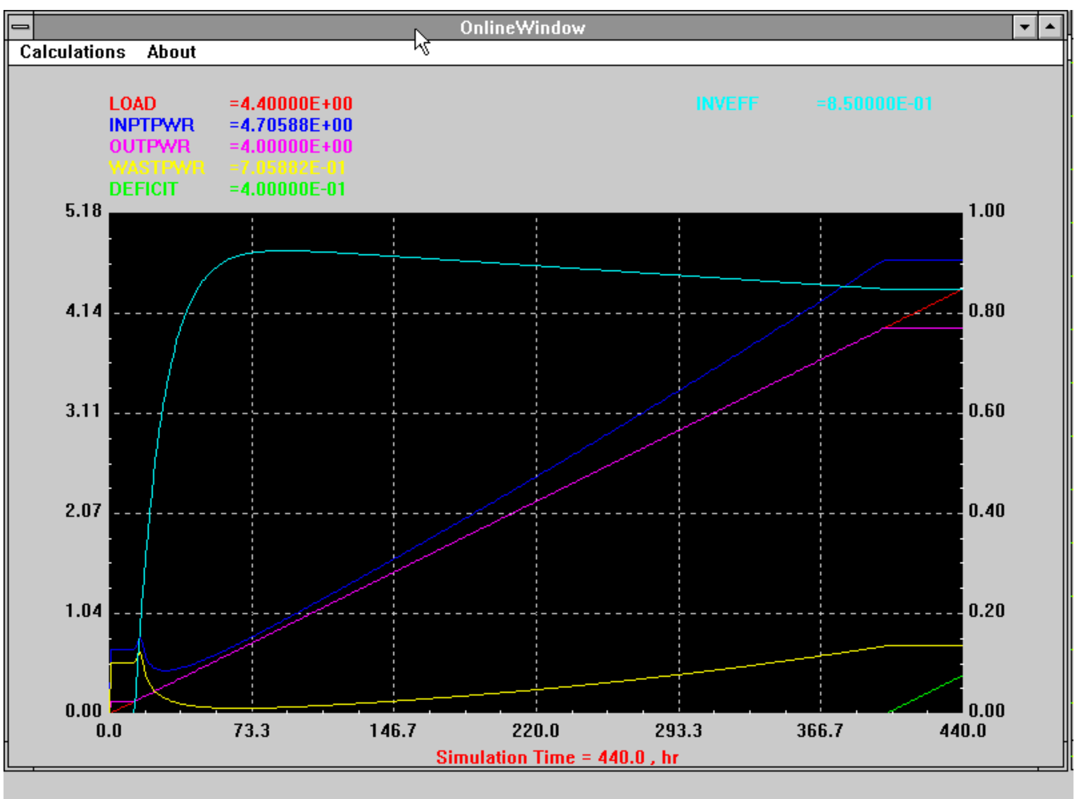

Figure 7.6 Example output of inverter demonstration simulation.

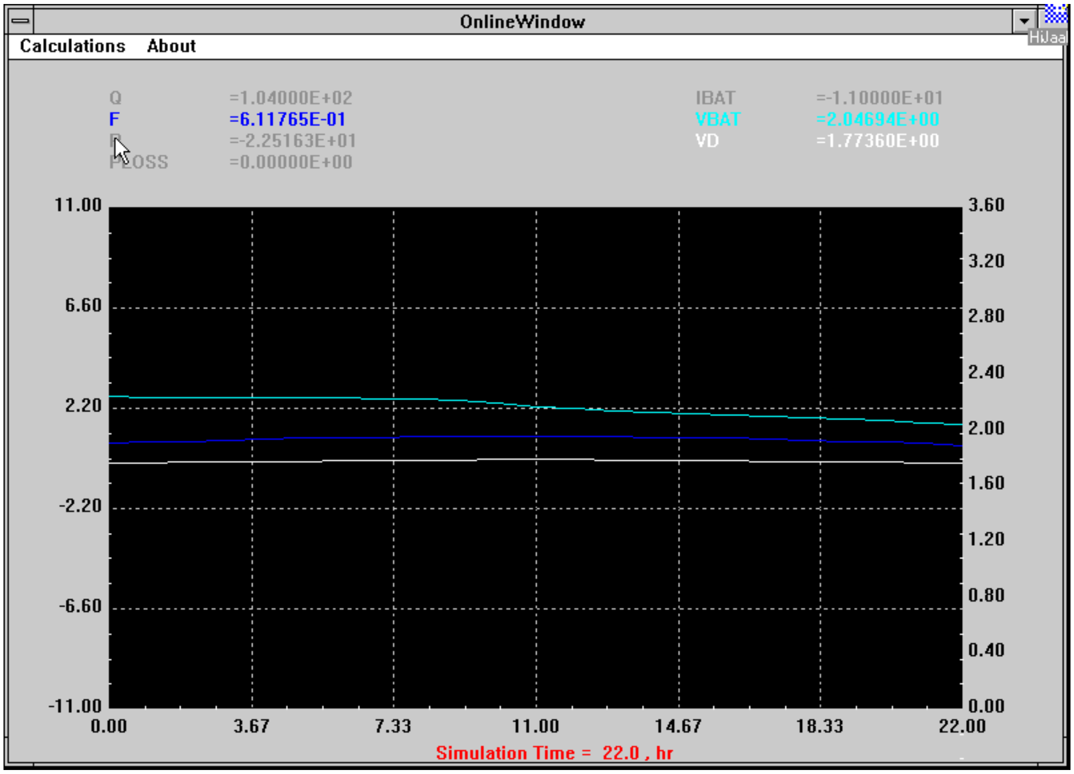

Figure 7.7 Typical battery operation.

7.1.8 *Verification of Hybrid Model*

Validation of hybrid model components was carried out by comparing the results given by the components to the operation of actual components. The operation of the dispatcher was taken to be validated from a logical basis. For the wind turbine and diesel generator components, this process simply involved a comparison of the simulated results to the input power curves and fuel-use curves. The wind turbine cluster and hybrid simulator required more detailed review.

Figure 7.8 is an example of a hybrid systems simulation employing all of the verified components.

7.2 Validation of Hybrid Model

Each of the newly developed components in UW-Hybrid was validated independently in Section 7.1. In this section, the performance of the integrated model is examined as it performs a simulation of a hybrid system installed in Wisconsin.

7.2.1 *Validation of Wind Turbine Cluster Component*

The operation of the wind turbine cluster component was compared to the operation of a real cluster, using field data. In this case, the cluster data employed was from the three-turbine demonstration project in Goodnoe Hills, Washington. Three MOD-2 2500 kW wind turbines were situated in a non-symmetric site plan. Table 7.1 lists the operating specifications of the MOD-2 wind turbines at the site.

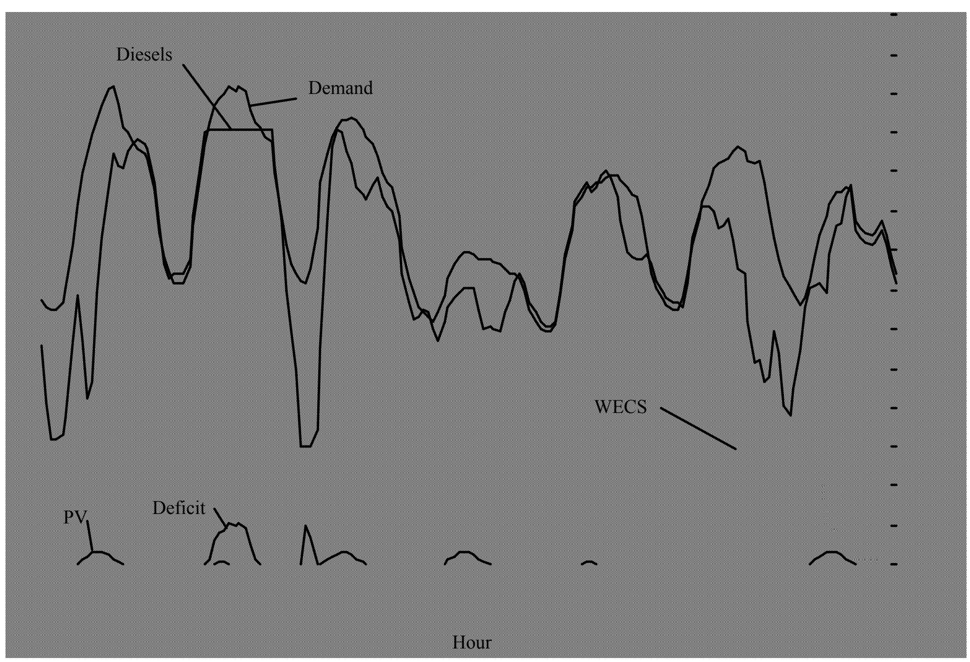

Figure 7.8 Simulated week of operation of hybrid system in Wisconsin.

Table 7.1 MOD-2 Specifications

Rotor Diameter	91.4 m
U cut-in	6.3 m/s
U rated	12.5 m/s
P rated	2500 kW
U cutout	21 m/s

The Goodnoe Hills site, operated by the Bonneville Power Administration, was extensively used for wake data collection and cluster effects analysis. This site was selected for this validation because of the quality and availability of pertinent data. Although there were only three wind turbines, two wake deficit/cluster effect pairings could be investigated because of the triangular layout: two turbines upwind at different distances from the downwind wind turbine. Figure 7.9 shows a site plan with each of the pairings,: Unit 1 is repeated downwind from Units 2 and 3 as Unit 1a and Unit 1b. The distance between Unit 1 and Unit 2 was 628 meters, or about 7 rotor diameters. The distance between Units 1 and 3 was about 946 meters, or about 10 rotor diameters.

The first validation was of the Veenhuizen and Lin wake model for the calculation of wind speed deficit in the wake. A turbine-coordinates data file was created for the pairings shown, and the turbine operating characteristics were input. Type 88 was modified to run a narrow range of directions (250 degrees SW up to 290 degrees NW) one degree at a time, producing the results shown in Figure 7.10.

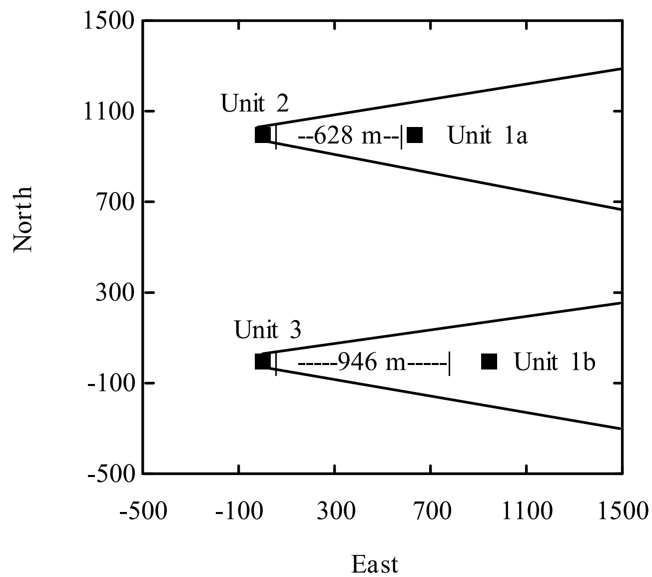

Figure 7.9 Goodnoe Hills wake effects pairings.

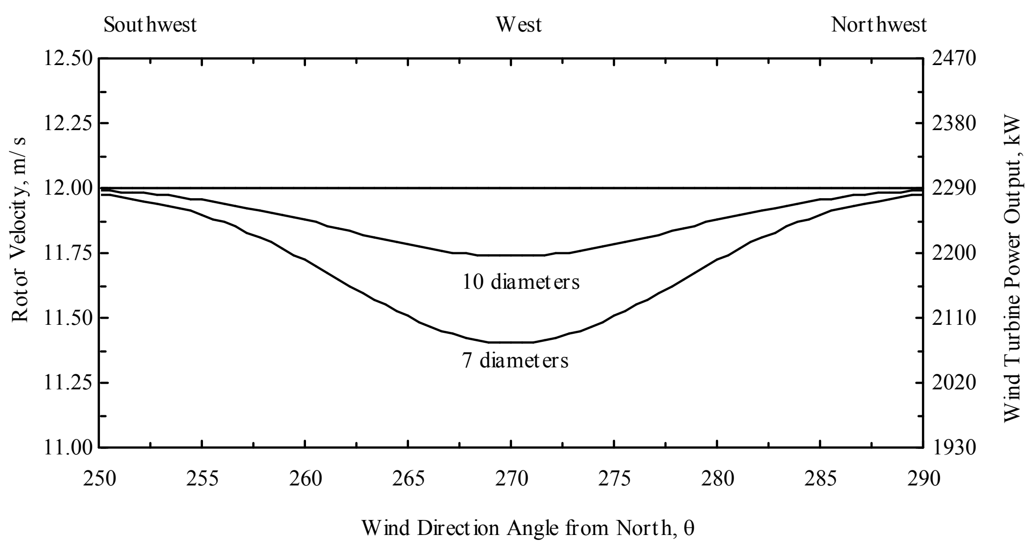

Figure 7.10 Modeled wind speed and power output of the wind turbine cluster at Goodnoe Hills, at 12 m/s.

Baker and Wade (1987) published wake velocity deficit data for distances of three, five, seven, and nine-diameters from the turbines at Goodnoe Hills. Wind speeds were measured using kite anemometers during a period when winds were aligned with the turbines and speeds averaged below rated (12.3 m/s). Baker and Wade published their wake data in a normalized format, with distances measured in meters rather than direction. In order to make the field data compatible with the output from Type 88, the field data were transformed into equivalent wind speed angles using a trigonometric approach. The position data and equivalent angle transformations are presented in Table 7.2.

The cluster model was run for the set of seven angles given in Table 7.2 and atmospheric conditions given the Baker and Wade reference. The wind speed deficits from the model were compared with the published data. The simulation results were in excellent agreement with the field data, as shown in Figure 7.11. Figure 7.12 shows a scatter plot of measured and predicted wind speed deficits, to complete the analysis of the model. The model slightly under predicted deficits in the \shoulders" of the wakes, and over predicted deficits at the center and edges. Considering the complexity of the analysis, the model performed well overall.

Calculation of wind speed deficit is only an interim step in the simulation using the wind turbine cluster model. Power output calculation accuracy is a more suitable test of the results, since accurate energy production estimation is the ultimate goal. Neustadter and Spera (1984) published an energy-based cluster effects study of the same Goodnoe Hills turbines as an effort to integrate wind speed deficit and power deficit studies of wind turbines in clusters. Neustadter and Spera conducted two tests, based on shutting the turbines off, then on, and comparing the energy production. The results indicated that, for a set of conditions, the power-deficit of Unit 1 in the wake of Unit 2 was approximately 10 percent.

The Goodnoe Hills setup was re-run using Neustadter and Spera's conditions, producing the results shown in Figure 7.13. The power loss estimates are in good agreement with the power loss data reported by Neustadter and Spera.

Table 7.2 Goodnoe Hills wake deficit data (Baker and Wade, 1987).

Obs.	Position (meters)	Equivalent Angle (degrees)	Speed Deficit (fraction)
1	-149.46	256.61	-0.01
2	-100.30	260.93	0.03
3	-53.50	265.13	0.11
4	1.06	270.10	0.20
5	49.51	274.51	0.09
6	100.68	279.11	0.02
7	146.05	283.09	-0.02

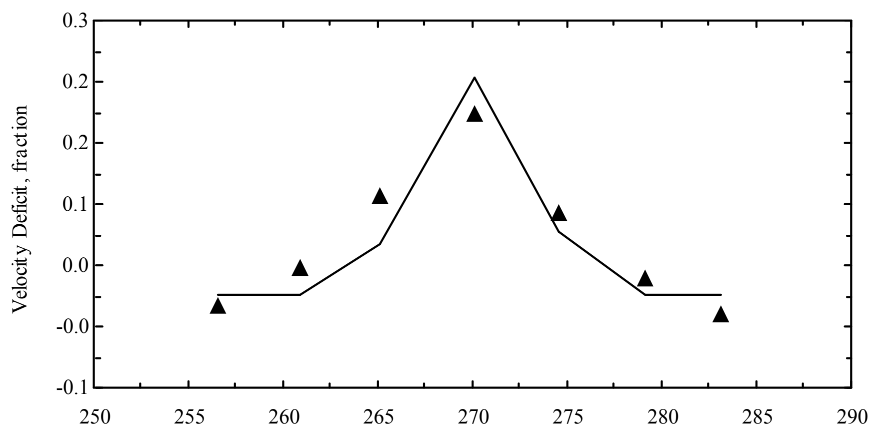

Figure 7.11 Comparison between cluster model and Goodnoe Hills published data.

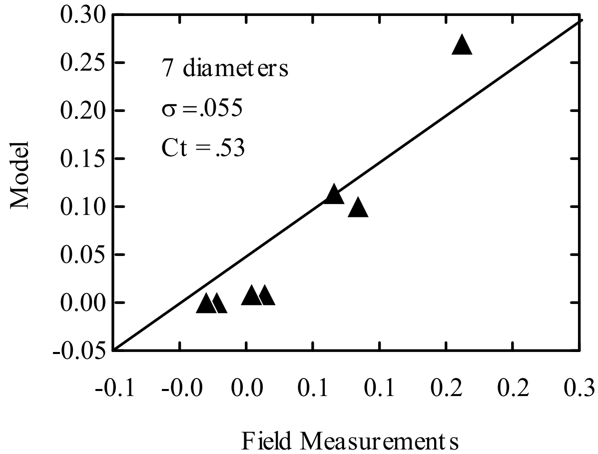

Figure 7.12 Correlation between cluster model and Goodnoe Hills published data.

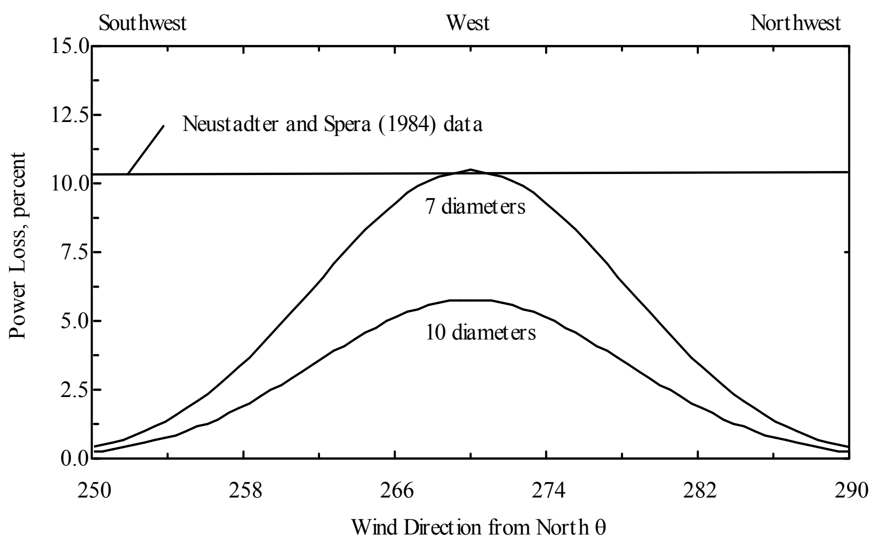

Figure 7.13 Power Loss estimates compared with power losses reported by Neustadter and Spera.

7.3 *UW-Hybrid Modeling: Case Study*

The hybrid model was run using actual loads data and *concurrent* weather data for Milwaukee, Wisconsin. These data were used previously in an examination of the benefits of water heating programs for utilities (Cragan, 1994). The data employed in this analysis represent weather and utility loads which occurred in the Wisconsin Electric Power Company (WEPCO) service area in 1991. Cragan observed that the WEPCO demand data exhibited high correlation with the weather data.

The WEPCO utility loads data for the 1991 were first normalized to a 300 kW peak, which is a representative size for a wind diesel hybrid power systems. Milwaukee weather data for 1991 were obtained without alteration. The TRNSED *.data file was altered to allow easy selection of the WEPCO weather and loads files with the TRNSED user interface.

In 1991, Milwaukee experienced its peak demand day on August 29. Cragan (1994) reviewed the weather and loads interactions for this period. For a hybrid system, it is assumed that demand would be expected to peak in a manner similar to the larger system. The maximum demand for the simulated hybrid system is 300 kWe. Examination of the sizes of diesels available in the diesel generator selection menus resulted in the selection of two Cummins 161 kWe units to serve the load. A baseline simulation of August 29 was performed, and is shown in Figure 7.14. All of the figures presented for the validation are screen captures of actual UW-Hybrid plots running under TRNSED.

For most of the day, both diesels were required to meet demand. The first unit operated at maximum for most of the day. The second unit followed the difference between the load met by the first diesel and demand. This behavior is the same as the behavior described in Figure 4.6, but for nonlinear demand.

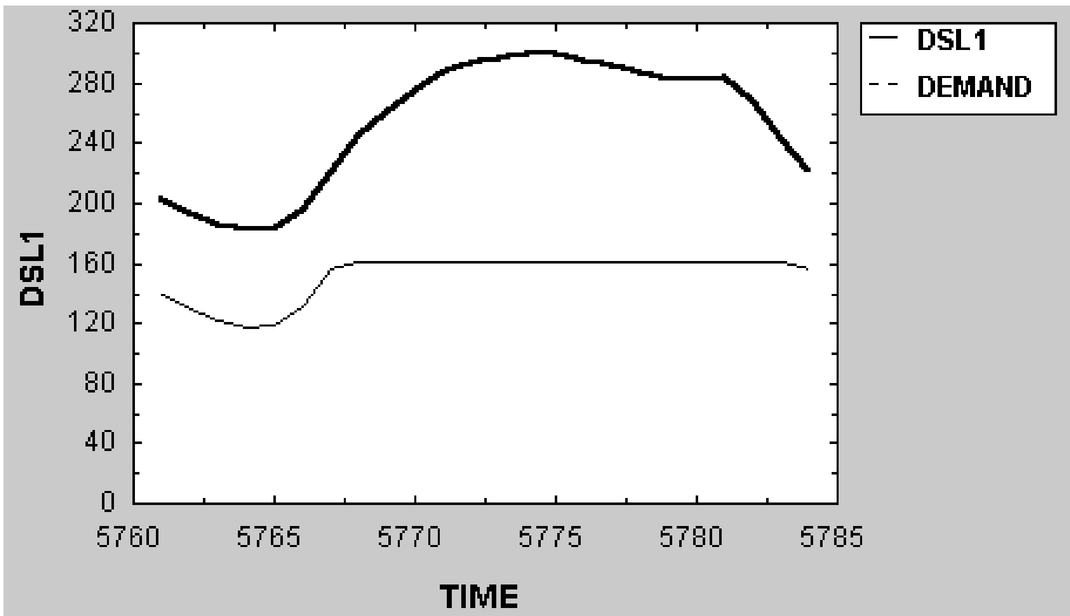

Figure 7.14 Two Cummins 161 kWe diesels are shown meeting demand.

The next step in the case study was to examine the potential benefit of a solar energy system, in this case PV generation. It has been shown (Cragan, 1995) that solar thermal is also able to provide a similar impact where there is electric water heating. Figure 7.15 shows the effect on the peak day by the introduction of 300 kWp of EP-50 PV modules. The PV modules are installed at a 45 degrees tilt and zero azimuth. The PV, as expected, is able to reduce the output of the diesels during midday. The second diesel is briefly shut down completely by the PV during the noon hour.

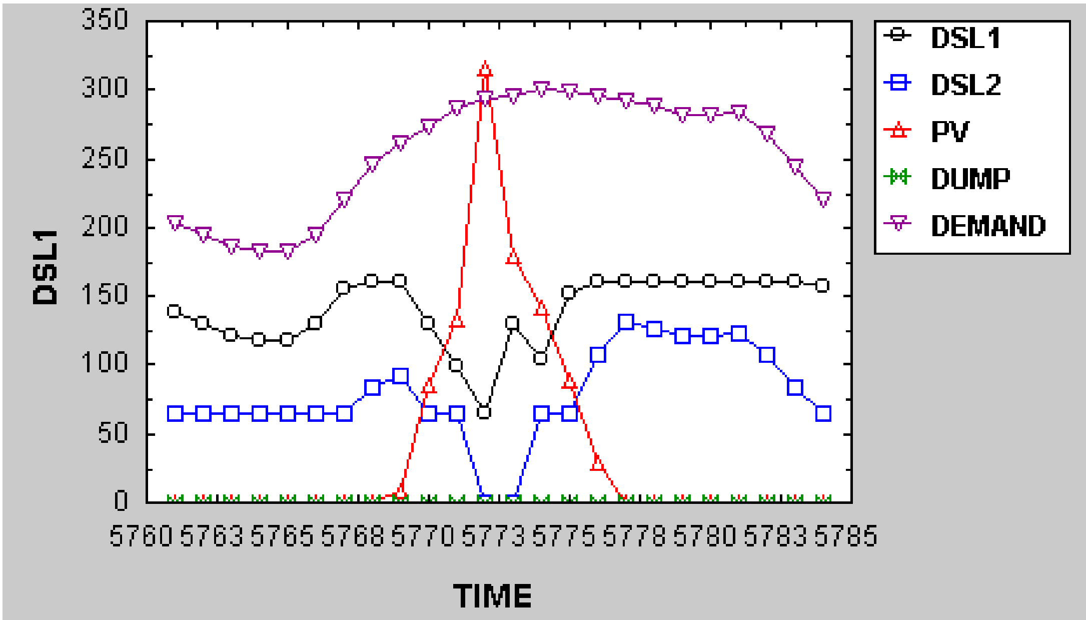

Figure 7.15 Effect of 300 kWp of PV on the base case generation.

The next generation option to consider for a hybrid power system is a wind turbine generator. A single AWT 275 kW wind turbine was added to the resource mix, and the PV was removed (a cluster was not used because the Milwaukee data did not include wind direction data).

Figure 7.16 illustrates the impact of a wind turbine on the operation of the diesels. The wind turbine contributes significantly to reduce apparent demand, operating at an average of approximately 200 kW, or 80 percent of rated output. In the early morning hours, the wind turbine actually output more power than demand, causing some energy to be dumped. Both diesels are displaced by the wind turbine during this period. During mid-morning, demand increases and the turbine output falls. For one hour both diesels are in operation. The second unit is in operation at its minimum allowable output of 64 kWe. For the remainder of the day, the wind turbine produces sufficient power so that the load is served by the single diesel and the wind turbine.

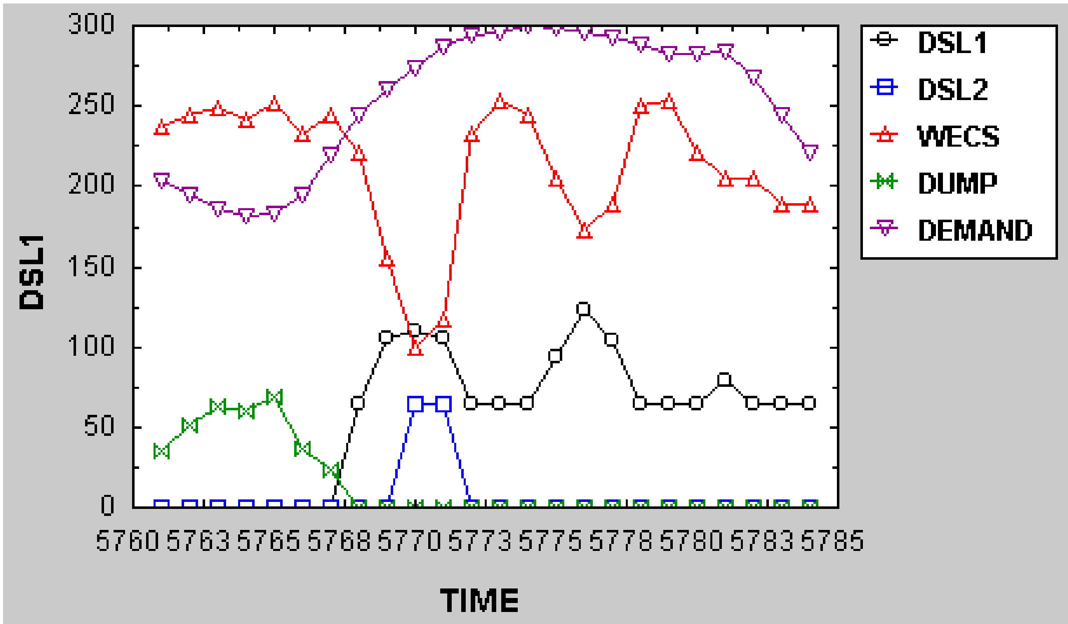

Figure 7.16 Effect of 275 kW of wind generation on the base case generation.

Figure 7.17 illustrates the combined potential of wind and solar generation on the hybrid power supply system. Much of the added solar generation appears to be contributing to dump energy. However, the additional PV contributed its energy at the one hour of the day when the wind turbine did not produce enough energy to avoid use of the second diesel. Significantly, the solar and wind were together able to allow half of the fossil fueled generation to remain idle during the peak day.

7.4 *Simulation Results*

This analysis of peak day operation in 1991 is not generally representative of year-to-year performance of hybrid systems and the contribution attributed to the renewable components. However, the example did demonstrate the ability of a combination of wind and solar to better match loads than either technology was able to do alone.

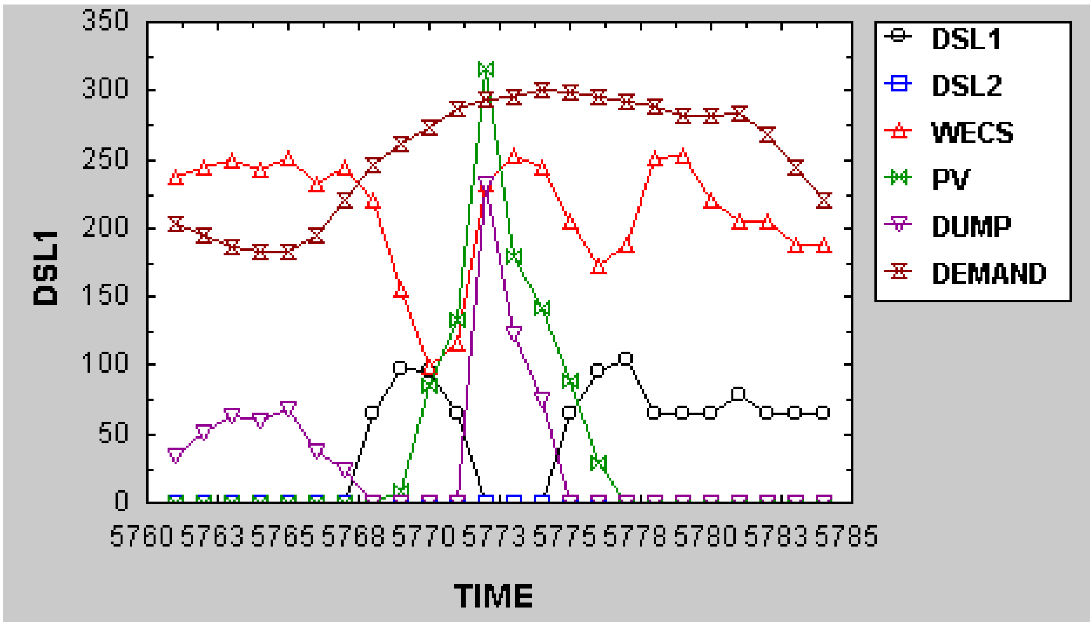

Figure 7.17 Combined potential of wind and solar generation

This case study of the examination of the contribution of the renewable components to reduce load in a hybrid system on the peak day of the year also demonstrated the efficacy of TRNSED and TRNSYS in the simulation of complex renewable power systems on the hybrid power supply system.