CHAPTER ONE

INTRODUCTION

Of all the forces of nature, I should think the wind contains the greatest amount of power.

– Abraham Lincoln, 1852

First costs of wind turbines have declined and reliability has improved to the extent that wind power systems are increasingly being considered for generation by utility planners in the midwest. Wind energy projects installed in Minnesota in 1995 and Michigan in 1996 reflect the maturity of the technology as a component in utility generation portfolios. Recently, Madison Gas and Electric Co. announced new wind monitoring activities in anticipation of someday installing wind turbines as a part of a \green" option for consumers. These developments reflect a history of interest and activity in the use of wind energy in Wisconsin.

1.1 Wind Energy Research in Wisconsin

Nationally, modern interest in wind electric energy grew significantly in the early 1980s based in part on early indicators of the technology's cost-effectiveness (Marsh, 1979) (Flaim and Hock, 1984). In Wisconsin, wind energy research and planning was initiated with a service-area resource assessment performed by Northern States Power Company (Kasmarik, 1981). Wind energy development in California and significant federal tax incentives spurred individuals to buy small wind turbines across the U.S (Gipe, 1983), including the midwest. Subsequently, Wisconsin Power & Light (WP&L) initiated a Wind Energy Research and Demonstration Program (DeWinkel, 1983b) when WP&L purchased and installed six wind turbines on customer premises in rural areas across the state. A small wind turbine manufacturing company, WindWorks, was established, and at one time was owned by WP&L, making the utility the first in the nation with a wind energy subsidiary. Figure 1.1 is a photograph of one of Windworks early wind turbines. Although WP&L's research program resulted in important operating data (DeWinkel, 1983a), (DeWinkel, 1985), the Windworks venture did not survive, and WP&L discontinued its involvement in the technology.

From 1984 through 1986, six Wisconsin electric utility companies jointly sponsored an anemometer loan program and a utility data collection program (Adamski, 1986). Thirty-five loan-program sites and twenty-six utility sites were operated at the time. Much of this data was incorporated in a wind atlas of the United States (Elliot, 1987). Wisconsin Electric Power Company (WEPCO) also monitored the impacts of small wind turbine generators on their system (Prothero, 1983) during this time. At the University of Wisconsin, Institute for Energy Studies graduate students (Kuffel, 1982 and 1984) studied wind flow across the state. Wind energy research and development activities in Wisconsin decreased with the expiration of federal tax incentives in 1985.

In the early 1990s, updated wind energy assessments of windy land (Elliot, 1991) identified the midwest as a region with excellent wind energy development potential. A report on the results of the state anemometer loan program was published in 1991 (Wisconsin

Energy Bureau, 1991). The Union of Concerned Scientists (UCS) then published a landmark study, *Powering the Midwest: Renewable Electricity for the Economy and the Environment* (Brower, 1993). The UCS study identified 2,387 MW of potential wind energy capacity in Wisconsin. The Renewable Energy Assistance Program (REAP) of the Department of Administration subsequently sponsored small wind monitoring projects in the state, including a preliminary examination of the near-shore wind resource of Western Lake Michigan (Owen, 1992 and 1993a), and monitoring of selected inland sites (Owen, 1995a and 1996).

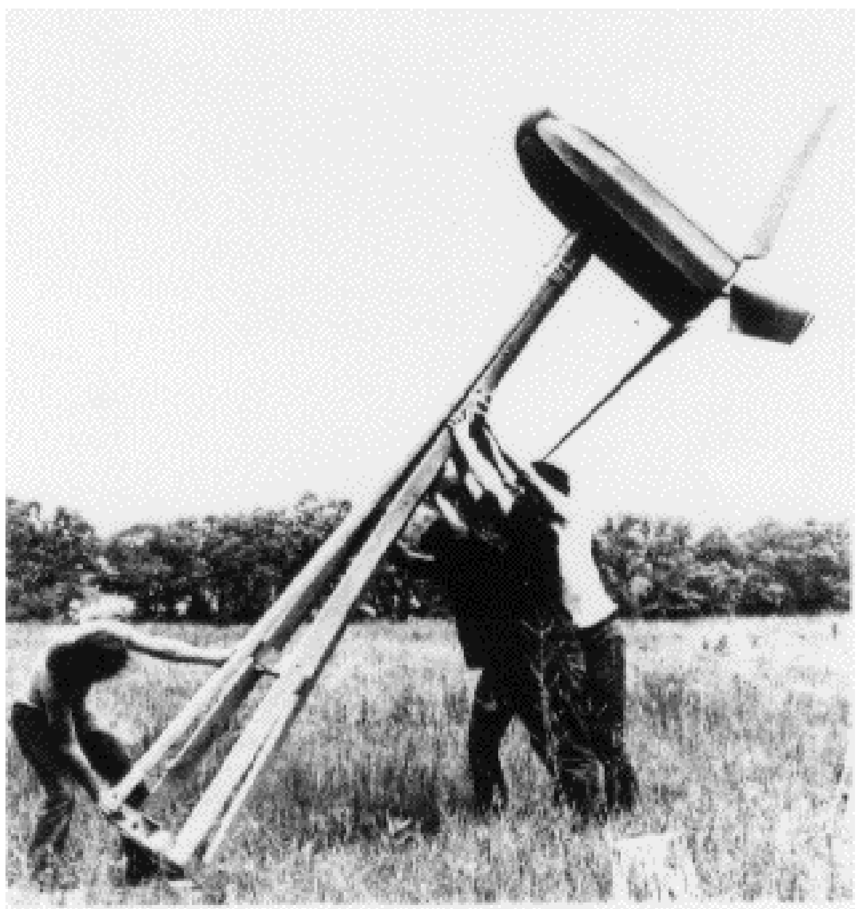

Figure 1.1 Wisconsin WindWorks turbine being raised.

1.1.1 *Recent Wind Energy Activity in Wisconsin*

Studies of local economic benefits (Clemmer, 1994) (Clemmer and Wichart, 1994), quantified external benefits of reduced emissions (Wan and Parsons, 1993), concern for climate change (Wisconsin DNR, 1991) and interest in deregulation has led to renewed interest in the use of wind by utility regulators (Hamrin and Rader, 1993), including in Wisconsin (Neitzel, 1993). Wisconsin utilities have contracted with Kenetech for wind monitoring (Kenetech, 1993) and have reported to the Public Service Commission of Wisconsin plans for 142 MW of wind energy capacity to be installed in the state (Wisconsin PSC, 1994). Wisconsin utilities expressed interest in wind technology appropriate for the region (Wind Energy Weekly, 1994). Renew Wisconsin and Wisconsin Pubic Service (WPS) have collaborated on a feasibility study of a 10 MW project in DePere (Owen 1993b), and research into distributed applications (Pupp, 1983) has led to a proposal to build a 20 MW wind plant in lieu of a proposed 138 kV transmission line (Owen, 1995b). In a related project, the National Renewable Energy Laboratory (NREL) sponsored research to refine estimates of available wind resources by taking into account proximity to transmission (Parsons, 1995). The likely outcome of all this research and activity is that wind projects will be built in Wisconsin in the near future.

1.2 Hybrid Systems Development

At the same time that Wisconsin utilities were considering grid-connected wind plants, other utilities across the United States, such as Arizona Public Service (Hickman, 1993), Southern California Edison (Quinlan, 1991) and a number of rural municipal utilities (Quinlan and Churchill, 1992) were developing off-grid programs for residential customers, primarily using PV generation (Stokes, 1992). The interest in providing remote power systems to individual customers was partially a response to significant growth in off-grid living, but also due to lower costs and competitive pressures for such services from alternative suppliers (including neighboring utilities). In most cases, the small power systems offered by these utilities included interfaces for engine generators (NEOS Corp., 1993).

Although the remote power systems offered by utilities in these programs can be described as hybrid systems, the internal combustion (IC) engine generators included with them are usually either gasoline or propane-fueled (Fowler, 1991a), and are not designed to operate a significant proportion of the time. The IC engine generators are used to charge the batteries or handle unusually large loads on an intermittent basis. It is anticipated, however, that as these utilities gain experience, and as the sizes of applications increase, wind-diesel-PV hybrids with full-time diesels will be considered.

1.2.1 *Hybrid Systems Around the World*

A significant number of hybrid diesel systems, with wind and/or PV, have been operating in various countries for several years. Table 1.1 lists systems documented by the International Energy Agency (IEA, 1994).

The IEA has developed a classification system, presented in Table 1.2. Table 1.3 lists the system architecture classes for each of the systems described Table 1.1. Note that only one of the systems has PV. However, the list is not comprehensive and does not include some newer systems (Durand, 1983 and 1984) (Green, 1994) that include PV modules.

Hybrid systems exhibit a significant diversity in the use of storage technologies. Although batteries are prevalent, pneumatic, hydraulic, pumped hydro (Veenhuizen, 1987) and flywheel (Davies, 1988) storage systems have been employed.

Table 1.1 Various hybrid power systems around the world.

Country	Location	Operating Dates	WT Size (kW)	Diesel Size (kW)	Load Range (kW)
Australia	Rottnest Island	1985-	20,50,55	110	90-460
Brazil	Fernand de Noronha	1986-	2 - 5	50	200 max
Canada	AWTS	1987-	37.5	2 - 50	0 - 100
" "	Calvert Island	1986-	2 - 3	12	0.5 - 3.5
" "	Cambridge Bay	1987-	4 - 25	4: 380 - 760	2375 max
" "	Ft. Severn	1985-	60	85, 125, 195	50 - 150
Cape Verde	Sal Island	1985-	55	-	-
" "	Santa Catarina	1987-	55	125	30 - 90
" "	Tarrafal	1987-	30	70	11 - 45
Denmark	Riso	1984-	55	35	
France	Domaine de Las Tours	1987-	10 - 12	152	100 max
Germany	Helgoland	1987-	1200	2 - 1200	1000-3000
" "	Schnittlingen	1983-	11	25	1 - 15
Greece	Kythnos Island	1984-	5 - 22	31.4	
Ireland	Cape Clear	1985-	2 - 30	65	15 - 100
" "	Inis Oirr	1981-	1 - 63	1-12, 1-26, 1-44	
Italy	Calbria	1986-	20	2 - 20	
Netherlands	ECN	1982-	2 - 30	50	50
Norway	Froeya	1989-	55	50	15 - 100
Spain	Bujarolez	1986-	25	16	
Sweden	Askeskar	1984-	1805	8.1	
" "	Chalmers University	1982-	22	20	
Switzerland	Martingy	1985-	160	130	60 - 80
UK	Fair Isle	1982-	55	1-20, 1-50	
" "	Falkland Islands	1987-	10	10	
" "	Lundy Island	1982-	55	3-6, 1-27	
" "	Machynileth	1986-	15	10	
" "	RAL	1983-	16	7	
" "	Shetland Islands	1988-	750	-	30 MW
U.S.	Block Island	1979-1982	150	1-225,400,500	1800 max
" "	Clayton, New Mexico	1977-1982	200	1-400,1700, 2-1000;3-1250	1000-3500

The IEA tables also do not show that, in many cases, the renewable components were retrofitted to existing diesel power systems. Retrofit applications appear to occur in approximately half of the installations. One reason for the high proportion of retrofits is that diesel engines in stationary applications can operate for decades, so that in many instances it is probably not cost-effective to replace the existing units for those more optimally sized for a hybrid configuration. Unfortunately, in this case, the sizes of the diesels are often larger than optimal for the hybrid configuration. Where there are multiple diesels, however, there exists the ability to alter dispatching in order to approach optimal load matching.

Table 1.2 The IEA classification system for hybrid power systems.

Wind Turbine Generator Type		Storage	
I	Induction	1	No storage
II	Synchronous	2	Battery
III	Induction or synchronous with ac/dc/ac power conversion	3	Flywheel
		4	Hydraulic / pneumatic
		5	Pumped storage
		6	End use
System Power Control		**Configuration**	
A	None	a	One WT / one diesel
B	Dump load	b	One WT / multiple diesels
C	Storage	c	Multiple WTs / one diesel
D	Load management	d	Multiple Wts / multiple diesels
E	Turbine rotor		

Hybrid systems are used in a variety of applications. Systems are operating in arid locations (Sodha, 1993), Arctic environments (Read, 1994), (Zhizhang, 1993) and offshore platforms (Mayer and Roberts, 1992). Applications range from village power systems to desalinization (Liu and Lin, 1987), water pumping (Clark, 1985), and refrigeration. Joint wind diesel technical workshops are held annually to bring together researchers in the field (AWEA and CanWEA, 1993, 1994, 1995).

1.2.2 *Hybrid Systems Modeling*

Much of the research in hybrid systems has been conducted in The United Kingdom (Infield, 1985), the United States, Canada (Green, 1994), Denmark (Aagaard and Lundsager, 1985) and China (Qi, 1993) (Liu and Lin, 1987). The American and Canadian Wind Energy Associations co-sponsor annual workshops and develop standards (AWEA, 1991).

Table 1.3 Architectures of various hybrid systems.

Country	Location	Storage	Load Control	WT Type	Power Control	Storage	Configuration	Notes
Australia	Rottnest Island	Yes-batteries	No	I	C	2	d	
Brazil	Fernand de Noronha	Yes-batteries	No	-	C	2	c	
Canada	AWTS	Yes-batt./fly.	Yes	I	B	2,3	b	
" "	Calvert Island	Yes-batteries	Yes	III	C	2	c	
" "	Cambridge Bay	No	No	I	A	1	d	w/PV
" "	Ft. Severn	No	No	II	A	1	b	
Cape Verde	Sal Island	Yes-batteries	Yes	-	B	6	a	
" "	Santa Catarina	Yes-batteries	Yes	III	C	2	a	
" "	Tarrafal	Yes-water	Yes	III	D,B	6	a	
Denmark	Riso	Yes-batt./fly.	Yes	I	B	2,3	a	
France	Domaine de Las Tours	No	No	I	E	1	c	
Germany	Helgoland	Yes-water	No	III	E	6	b	
" "	Schnittlingen	No	Yes	II	B,D	1	a	
Greece	Kythnos Island	Yes-batteries	Yes	I	B,E	2	c	
Ireland	Cape Clear	Yes-batteries	No	I	C,E	2	c	
" "	Inis Oirr	No	No	II	D	1	b	
Italy	Calbria	Yes-batteries	No	III	B,C	2	b	
Netherlands	ECN	Yes-batteries	Yes	III	B	2	c	
Norway	Froeya	Yes-batteries	No	I	B,C	2	a	
Spain	Bujarolez	Yes-water	No	II	B	6	a	
Sweden	Askeskar	Yes-batteries	No	III	B,C	2,6	a	
" "	Chalmers University	Yes-batt./fly.	No	III	B,C	2,3	a	
Switzerland	Martingy	No	Yes	I	B	1	a	
UK	Fair Isle	No	Yes	II	B,D	6	b	Biogas fuel input
" "	Falkland Islands	Yes-batteries		III	C	2	a	
" "	Lundy Island	No	Yes	I	B,D	6	b	
" "	Machynileth	Yes-hydraulic	Yes	II	C	4	a	
" "	RAL	Yes-flywheel	Yes	II	B	3	a	
" "	Shetland Islands	No	No	II	A	1	b	
U.S.	Block Island	No	No	II	A	1	b	
" "	Clayton, New Mexico	No	No	II	A	1	b	

In the U.S., most of the research funding in hybrid systems has gone to the University of Massachusetts (UMass) programs (Stein, 1988) (Manwell and McGowan, 1990) through projects sponsored by NREL. UMass produced its first time-series software simulator, HYBRID1, in 1990 (Manwell, 1990), and in June 1996 released an application designed for general use, HYBRID2 (Green and Manwell, 1995) (Manwell, 1996) (Baring-Gould, 1994)

(NREL, 1996). Sizing applications have also been sponsored by NREL, including an upgrade to SOLSTOR solar energy model, SOLSTOR W/D, developed by AeroVironment (Zambrano and Lindberg, 1988). Last year, NREL reported on its hybrid systems sizing application program, HOMER (Lillienthal and Flowers, 1995).

All of the wind-diesel models reviewed, including HYBRID1, HYBRID2, SOLSTOR W/D, and HOMER, and a number of university research applications, are large, non-modular computer codes. Although most attempt to provide configurational flexibility, none are modular to the extent that distinct elements can be separately created and linked by the user.

1.2.3 *Diesel Engine Research*

Diesel engine research has been ongoing since Rudolf Diesel received his patent for the development of the diesel cycle engine in 1893 (El-Wakil, 1984). Diesel engines used in vehicles are variable speed, whereas in static power configurations the engines operate at fixed speed. In general, larger power diesels operate efficiently at lower speeds, but in most hybrid applications employing smaller engines, diesels operate at relatively high speeds. Judge (1957) has systematically characterized the fuel consumption and efficiency characteristics of high-speed diesels. Lilly's (1984) *Diesel Engine Reference Book* lists many of the models useful for systems sized below 1 MW capacity. Heywood (1989) has published a comprehensive book on IC engine fundamentals.

1.2.4 *Battery Research*

Early battery models were based on a combination of the work by Shepard, and that of Zimmerman and Peterson, integrated by Evans at the University of Wisconsin (Eckstein, 1990). These models were sufficient for properly designed PV applications, but did not include variability in efficiency as a function of charge current, nor temperature effects.

Researchers at Cuidad University in Madrid, Spain have been systematically modeling the behavior of batteries in PV applications (Coppetti, et al., 1993) (Castaner, 1995), to account for these effects. Researchers at UMass have also created a Kinetic Battery Model, or "KiBaM", as well (Manwell, 1993 and 1995), to account for these important performance factors.

1.2.5 *Solar and PV Modeling*

The solar PV modeling components used in the hybrid simulations are those updated by Al-Ibrahim (1996), based on work by Eckstein (1990) and Furler (1993). The PV components, in turn, utilize a solar radiation processing component based on algorithms published by Duffie and Beckman (1991). The UMass PV models and solar data processor are also based on the same research conducted at the University of Wisconsin-Madison.

1.2.6 *Power Conversion Modeling*

AC/DC energy converter modeling has historically been a simple (Paul, 1981) curve of efficiency as a function of output (load). The UMass model (Manwell, 1996) also linearly interpolates values of parameters to calculate efficiency. A more representative non-linear model has been employed by Jennings (1996) based on the work of Philips.

1.3 Wind Systems Modeling

Wind turbines have been around for a thousand years. The first recognizable windmills appeared in Persia for powering irrigation systems in 900 B.C. (Torrey, 1976). Much of the early work in modern wind science is attributed to the Dutch, beginning in the 1500s. Windmills were put to use as water pumpers in the early days of the settling of the United

States. Without windmills, the great steam trains that helped to settle the American West would not have had water for their boilers.

Electrical wind machines made their mark at the beginning of the 20th century. Much of the area of the U.S. was not electrified, and windmills were commonly used to charge batteries for farmers' radios. It was during this time that Jacobs and Windcharger models earned their reputations. Rural electrification greatly reduced the numbers of electrical wind turbines after the Great Depression.

During the early 1940s, the S. Morgan Smith Company sponsored MIT faculty and engineers, led by Palmer Cosslett Putnam, to develop a 1.25 MW wind turbine prototype. The Smith Putnam wind turbine was built and operated in Vermont for approximately 18 months, and demonstrated the feasibility of large utility-connected wind turbines (Koeppl, 1982).

Much of the design work for the Smith-Putnam was attributed to the aerodynamic theory developed by von Karman, Flettner, and Honneff, as well as the airscrew theory developed by Glauert and applied by Betz to turbines. After Smith-Putnam, significant research and development activity did not resume until the late 1970s in response to the oil crises of the period (Golding, 1978). In the United States, important new theoretical work was produced by Wilson and Lissaman (Wilson and Lissaman, 1974) (Wilson, 1976), and in Denmark, field research commenced with construction of the Nibe turbines (Taylor, 1985). Wilson and Lissaman's work was eventually codified into the PROP wind turbine rotor computer program, which was widely used in the early 1980s.

1.3.1 *Energy Production Estimation*

Before the general availability of computers, most wind energy modeling consisted of summing the product of wind turbine power curve values (kW) by wind speed frequencies (hours) to calculate annual kWh (Lipman, 1982). Since most data at the time were not available in time-series formats, several methodologies were employed to create the wind speed frequency distributions. The two most often employed were the Weibull (Weibull, 1951) and a subset of the Weibull originally developed by Rayleigh (Corotis, 1980). The Weibull is a two-parameter function, where one parameter controls skewness and the other controls kurtosis. The Rayleigh is a Weibull with fixed skewness; it is a single-parameter function, with that parameter being annual mean wind speed. Both models came into wide use, to the extent that they became incorporated into industry standards for reporting estimated annual energy production of a wind turbine as a function of annual average wind speed (AWEA 1988b). The use of distributions became such common practice that most time-series data were routinely reduced to wind speed frequency distribution data sets for turbine energy studies (Justus, 1976).

1.3.2 *Power Curve Estimation*

Collection of power curves for wind turbines has always been problematic. Due to their size, wind turbines cannot be tested under laboratory conditions. Rather, turbines are tested in the field, where ambient conditions are carefully monitored. Standard practice is to locate an anemometer at hub height, (or rotor center height, in the case of vertical axis turbines), and collect wind speed, direction, temperature and pressure data in the flow directly upwind of the rotor (IEA, 1982) (AWEA 1986). Nevertheless, the resultant data show a high amount of scatter. The scatter is due to the fact that the anemometer is essentially a point source measurement device, while the rotor averages the flow, exhibiting hysteresis and reduced high frequency response. This scatter in wind turbine power curve data has historically been reduced through a binning process. Prior to binning, data are usually normalized to standard sea-level air density value using ratio methods (Hansen, 1980). Recent testing of variable-speed turbines has resulted in proposals to slightly modify these methods to better account for the power regulation methodologies (Frandsen, 1994).

In recent years, a greater proportion of modeling work has gone into aerodynamics, loads (Veers, 1994) and power conditioning. This aerodynamics work has resulted in a better understanding of the effect of wind speed variation, both long term and short term. Long term (interannual) variation (Justus, 1978) causes significant variation in annual energy production in some regions. Short term variation (turbulence) has been found to be one of the prime factors in determining rotor life (Connell 1985 and 1988). Energy production, on the other hand, is not very sensitive to turbulence, due to the hourly and greater time-scales employed and the angular momentum integrating characteristics of the rotor.

1.3.3 *Cluster Modeling*

The original modeling of wind turbine clusters (often called arrays) is attributed to P.B.S. Lissaman at AeroVironment (AV), who in the late 1970s foresaw the need to understand the cumulative effects of multiple turbine installations (Lissaman, 1982). Lissaman's work was sponsored by several federal grants (Lissaman, 1985) culminating in the development of the AVENU model in 1988 (Lissaman, 1988). Subsequently, considerable research in cluster effects was undertaken in Europe, especially in the area of data collection (Ainslie, 1988). The European work was especially significant in the characterization of in-wake turbulence (Crespo, 1988) (Builtjes and Vermeulen 1992) (Luken, 1992).

During this time, federal research contracts were also awarded to Oregon State University (OSU) for wake data collection (Baker and Wade, 1984 and 1987), and United Industries Corporation (UIC) for applying and validating the Lissaman models and available data in a computer model of wind cluster performance (Veenhuizen and Lin 1985).

Considerable effort was expended in both Europe and the United States to extend Lissaman's cluster models to include the effects of wind flow over complex terrain. These efforts culminated in several large computer models of complex terrain wind flow and wake interactions. The U.S. government sponsored the NOABL model, and the European Community sponsored methods developed by Jackson and Hunt (Jackson-Hunt methods were also employed in AeroVironment in their AVENU software). Unfortunately, validation projects of both models showed significant error in estimating energy production in complex terrain (Barnard, 1990) (Elliot 1993) (Kline, 1993). Intensive in-field research of large wind projects (Kelley, 1989) yielded insights into effects not taken into account by the models, including nocturnal katabatic flow conditions (cold night air draining down the side of nearby mountains). Since then, the priority for modeling wind flows in complex terrain has been significantly reduced.

Nevertheless, validation work continued on the UIC cluster model, which showed relatively good results (Veenhuizen, 1988) (Nierenberg, 1989) (Simon, 1992). Fortunately, the UIC model is not unreasonable for use in feasibility studies of potential projects in Wisconsin, since such projects will probably be composed of a small number of wind turbines, and are likely to be sited on relatively flat terrain.

1.3.4 *Wind Resource Modeling Using GIS*

The greatest progress in wind energy resource modeling in the last few years has not involved turbine technology, *per se*, but the application of GIS methods for calculating regional wind potential (EPRI, 1994). GIS systems are computer hardware and software systems designed to manipulate geographic data (Aronoff, 1995). By mathematically manipulating rasterized digital terrain maps, wind atlas data, transmission line locations and exclusion information, researchers have been able to systematically create much more detailed wind resource siting maps of New York State (Bailey, 1992), Texas (McCarty, 1994), and Wisconsin (Withrow, 1996).

1.4 Motivation for Research

The wind industry has traditionally performed energy analyses in the ``frequency domain'', using wind turbine power curves and wind speed frequency distributions to calculate the energy delivered by a turbine or project for a month or year. However, assessment of wind power potential is difficult due to a number of factors, such as the need to adjust wind manufacturer's data to different site conditions, and the need to consider the effect of wind turbine power on electrical demand. Utility valuation of renewables has therefore become more critically sensitive to the time of delivery of renewables-based electrical energy.

Utilization of "time-domain" instead of "frequency domain" modeling approaches reflects a recent shift in wind power assessment to this utility value perspective. For this reason, time-series based analytic tools are expected to be required for utility feasibility assessment. However, the availability of time-series software tools designed for the analysis of wind is limited. A literature search did not result in the discovery of available time-series turbine performance models (other than the simple component in the Hybrid2 model) or any time-series cluster performance models. The goal of this research has been to develop these tools and apply them in a challenging context, in this case|hybrid systems. Hybrid systems are an excellent application for the exercise of these new component simulations.

One of the most often proposed applications for renewable energy systems has been in combination with diesel-fueled facilities. The intended role of a renewable component in such a hybrid system is to reduce fuel requirements and overall costs. In many areas, the expense and logistic effort required for diesel fuel deliveries can be very high. In most cases, wind turbines and/or photovoltaic modules are employed, often where diesels are already operating.

The potential economic benefit of hybrid power systems is offset, to some extent, by associated increases in capital cost and complexity. Technical challenges include power management strategies and maximizing the contributions of the renewable energy devices. An effective approach to understanding hybrid power systems is to simulate their operation using time-series weather and loads data from a specific location. A flexible, modular approach to their simulation allows researchers the ability to design in software and configuration which may be found in the field.

A secondary objective of this work was to improve existing storage battery and data-reading software for use in the hybrid application of the new wind power components, such as loads data reading components. In addition, it is hoped that application of the hybrid simulation in a case study will demonstrate the value of a modular philosophy for optimizing system design, and address an interest in the potential for hybrid configurations of solar and wind systems to better match loads at a candidate site.

1.5 Modeling in TRNSYS and TRNSED

TRNSYS (pronounced "transis"), commercially available since 1975, was initially designed to simulate the transient performance of thermal energy systems. Each physical component in a system, such as a pump or solar collector, is represented by a FORTRAN subroutine. The subroutines are then linked into a compiled executable code. An input text file coordinates the linking of the subroutines, and also describes the performance parameters for each subroutine.

All TRNSYS users have access to the FORTRAN source code and can create their own subroutines and simulations of physical systems. This open approach has resulted in a diversity of simulations, from solar photovoltaic (PV) pumps and vehicles, to dairy farms, to regional utility dispatching analyses (Cragan, 1995).

In recent years, TRNSYS has become more widely used in building energy analyses (Thornton, 1991), PV systems analyses (Al-Ibrahim, 1996), and utility renewables planning (Trzesnieski, 1996). TRNSYS is also used extensively in Europe, with development and distribution activities in Sweden, France, Germany and Belgium. Two separate front-end applications also now run TRNSYS code under different user-interfaces (SEL, 1996a).

1.5.1 *TRNSYS*

TRNSYS relies on a modular approach to model energy systems and requires an input file in which the user specifies the components that constitute the system, and the manner in which they are connected. Each of the TRNSYS components has inputs and outputs which represent, for example, the weather data, energy flows, and control signals of the physical counterparts. All the subroutines are linked and then controlled by the main TRNSYS program. The input file contains parameters and initial values for each system component, and describes how the different system components are linked together. For each component, a number of parameters (variables that do not change with time), inputs (variables that change with time and may come from other components) and initial values are entered into the input file.

TRNSYS users are able, through this input file, to completely describe and monitor interactions among system components. The process of system simulation is therefore open to the user and straightforward. Built-in capabilities include plotting routines, output-file data routines, on-screen plotting during processing, and parametric operation. TRNSYS and its component applications run in DOS as well as Windows® 3.1, 95, and NT.

1.5.2 *TRNSHELL*

A user initiates the simulation process by entering an editing environment program called TRNSHELL (pronounced "transhell"). Figure 1.2 shows an example TRNSHELL screen. This editing environment includes cut/copy/paste and search/replace options; context sensitive help; plotting routines; and houses the various TRNSYS utilities, including video, printing and compiler settings. The user can create a new input file or edit existing input files to define a simulation. The user then runs the simulation by selecting "Calculate" from a pull-down menu.

During the simulation creation phase of a project, TRNSHELL is used for debugging, for viewing run-time plots and for viewing post-simulation plots of selected variables. TRNSHELL is also used to create the help files for the TRNSED (described in the next section) version of the energy system components.

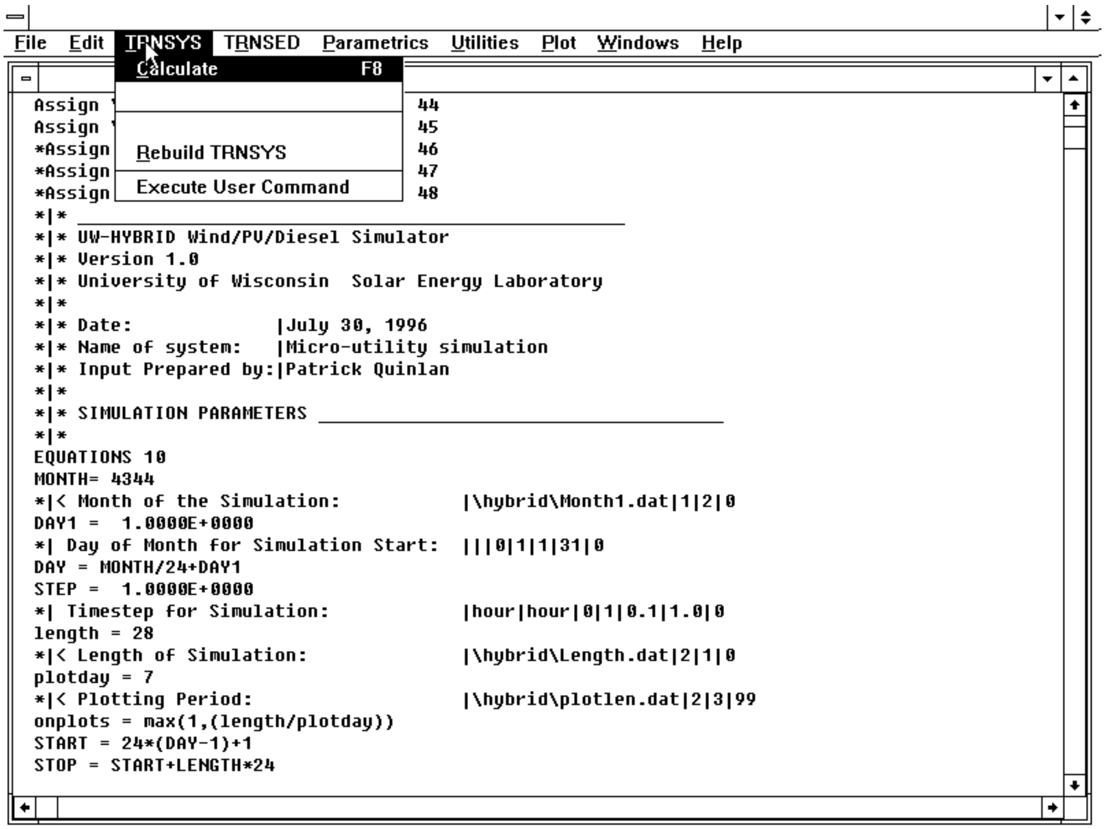

Figure 1.2 Example TRNSHELL screen.

1.5.3 *TRNSED*

With the specification of input files complete, a user may wish to distribute a simulation program to users who may have less expertise in the operation of TRNSYS. In this case, a run-time front-end application, TRNSED (pronounced "transed"), can be employed. The expert user can choose which variables are available for editing in the TRNSED input file. Detailed help, unit conversion, and input checking for each item is provided. A screen from a TRNSED user interface is shown in Figure 1.3. In many instances, a user may wish to explore the sensitivity of system performance on an input variable. If so, the user may post any of the TRNSYS variables displayed in the user-interface to a Parametric Table. By selecting the number of runs and a range across the runs, the user has the capability to create a "batch" of simulations. This allows the user to set up unattended repeated operation of a complex simulation, or to carry out detailed optimization studies. Plotting and output data capabilities can be applied to the Parametric Table results to allow examination of results across runs.

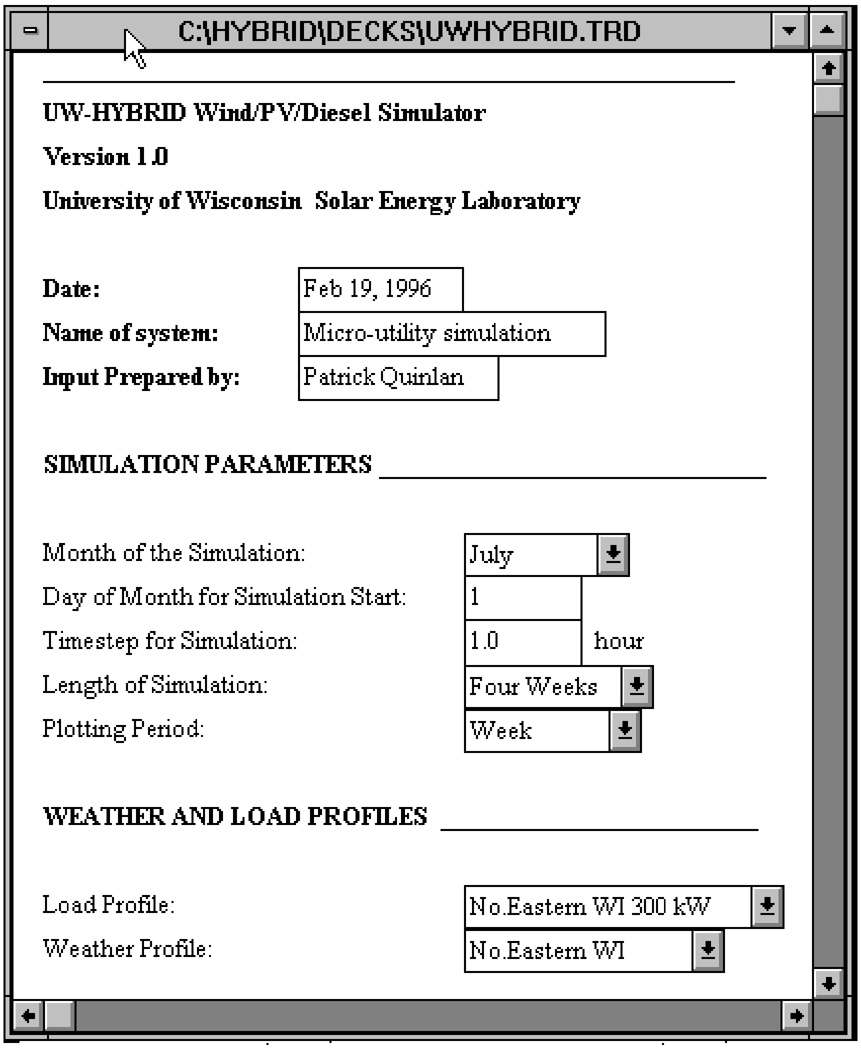

Figure 1.3. Example screen from a TRNSED user interface.

TRNSYS also allows the display of ten variable values in a plotting window while a simulation progresses. The on-line plotting software allows the user to pause the TRNSYS simulation while running, change the scale of the plot, hide one or more variables on the plot, and zoom into the display.

1.5.4 *TRNSYS Component Libraries*

TRNSYS component models are available in two major libraries. The first is provided with the program, and contains the components developed at the Solar Energy Laboratory. This library includes the core components used in most simulations, as well as more complex components developed at SEL. The second source of information is the library of "user-written" components shared with SEL by the user community. This library is maintained on the Internet (SEL 1996b). Component models from these libraries, which are used in hybrid power systems simulations, are:

- TMY Data Reader — *Reads in weather data from a "Typical Meteorological Year" data file.*
- Text File Reader — *Reads in loads values and other text file data.*
- Hourly Printer — *Sends values of variables to an output file each hour.*
- Solar Radiation Processor — *Determines temperature and incident solar radiation.*
- Photovoltaic Array — *Calculates PV array power each hour.*
- Storage Battery — *Simulates operation of a lead-acid battery.*
- On-Line Plotter — *Shows values on screen during simulation.*
- Quantity Integrator — *Integrates hourly data for monthly results.*
- Histogram — *Creates histograms of selected variables.*

TRNSYS and its component libraries constitute a mature, comprehensive environment for the time series simulation of hybrid power systems, including the wind and other components which are sensitive to weather and time-dependent loads.