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ANALYSIS OF REMOTE SITE ENERGY STORAGE AND GENERATION SYSTEMS

LEVEL II

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report presents the results of an investigation and analysis of energy storage systems and alternate energy sources for remote site applications. The first phase of the effort centered on the broad based study of hydrogen storage, thermal storage, batteries, and flywheels as energy storage systems along with wind turbine, solar photovoltaic, and solar thermionic energy converters. A wind turbine battery system was recommended based on performance, cost and availability. Effort under the second phase of the program concentrated on a system using two separate nominal eight kilowatt wind turbine modules in con-

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20. Abstract (continued)

junction with a lead-acid battery energy storage unit. The system was specified to operate in conjunction with an existing power grid system located at Bar Main, Barter Island, Alaska. Specific system concepts and recommendations are presented with supporting analyses. A design checklist is included with specific items for consideration in the preparation of a design specification.

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PREFACE

This report documents work performed during the period July 1978 to June 1979 by the University of Dayton under the AFAPL Senior Investigator Program for the HQ AFESC Engineering and Services Laboratory. The authors of the report are J. N. Crisp, J. D. Pinson, L. A. Anderson, and W. S. Bishop. The Project Engineer was Dr Tom Mahefkey, AFAPL/POE.

This report has been reviewed by the Information Office (OI) and is releasable to the National Technical Information Service (NTIS). At NTIS it will be available to the general public, including foreign nations.

This report has been reviewed and is approved for publication.

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SECTION 1
INTRODUCTION

1.1 PURPOSE AND SCOPE

The primary purpose of this investigation was to conduct an engineering analysis to establish the design criteria for a remote site energy storage and generation system. The system was required to meet a continuous output power requirement for remote sites utilizing alternate energy systems. The Air Force has found that providing power to remote sites with existing equipment requires an inordinate amount of manpower and logistics support. The amount of funding required for the number of sites currently in use by the Air Force is a significant drain on resources. If power systems can be utilized that require little maintenance and/or logistics support, the savings to the Air Force in terms of manpower and funds would be great. The work was divided into two phases, the first phase was a generalized study and analysis of potential remote site alternate energy and energy storage systems. The second phase which built upon the results and recommendations of Phase I concentrated on a specific location and a specified wind turbine/battery energy storage combination.

1.1.1 Phase I - General Analysis

The study was initiated by a thorough literature search to identify characteristics of candidate energy storage and alternate energy supply systems, and determine the algorithm for selection of an optimum energy storage system when an alternate energy supply system was specified. Results were then reviewed and recommendations were made for the optimum energy storage system for a specified wind/solar generator system.

The scope of the effort for the analysis was restricted by the following constraints and/or guidelines; as specified by the Air Force:

- Storage Output Power Required: 10 KW_e, continuous output power with a peaking capability of 20 KW_e for 12 hours, with an emergency storage capability of 240 kilowatt hours in the event of interruption of energy converter output.

- Storage Output Form and Conditioning: 208 V, 60 Hz, 3 phase, regulated ±5 percent per phase over the entire load range.

- Storage Output Power Module: The storage system shall be designed and analyzed in module form (e.g. four 5 KW_e for 12 hours modules) to allow flexibility.

- Storage Candidate Systems: Energy storage candidates to be considered shall include, but not be limited to, conventional lead-acid (baseline) batteries, nickel-hydrogen batteries, and advanced sulfur batteries.

- Design Goals: Design goals include unattended automated operation with a maximum one week per year service period, and air or truck transportable assemblies. Reliability, survivability, and initial and operating costs will also be considered.

- Alternate Energy Power Supply: The alternate energy power supply systems which shall be considered are wind, solar thermal, and solar photovoltaic.

1.1.2 Phase II - Specific Location Analysis

This phase built upon the results and recommendations of the preceding phase. This effort concentrated on a system consisting of two wind turbines and a lead acid storage battery for a specified Alaska location. The scope of Phase II of the analysis was governed by the following guidance and constraints:

- Wind Turbine Modules: Two wind turbines of a nominal 8 $kilowatt_e$ rating were to be used.

- Energy Storage: The energy storage system was specified to be lead acid batteries.

- Location: The location was specified to be Bar Main at Barter Island, Alaska.
- Load: The system had to be compatible with an existing power grid and its' loads.

SECTION 2

PHASE I - GENERAL ANALYSIS OF REMOTE SITE ENERGY STORAGE AND GENERATION SYSTEMS

2.1 SURVEY AND ANALYSIS OF CANDIDATE STORAGE AND GENERATION SYSTEM

A selection algorithm for remote site energy storage was developed with optional alternate energy supply. Converters using wind power, solar photovoltaic power, and solar thermionic power are considered and compared for remote site energy generation. Candidate systems were ranked with respect to remote site utilization in both short term and long term applications. A power conditioning approach is developed using a modular concept.

2.1.1 Energy Storage

2.1.1.1 Selection Algorithm

The process used to evaluate the candidate energy storage systems consisted of the following seven steps. First, the power system output requirements were established based on the work statement requirements. Second, using the established power requirements, candidate energy converters and their characteristics and conceptual system block diagrams were drawn (two in this case). Third, the energy storage portion of the conceptual system block diagrams was expanded in detail to define all necessary functions. Fourth, a relationship was established among output, stored, and generated power to identify critical parameters. Fifth, performance data was gathered on the critical parameters for each component of the energy storage subsystem block diagram in sufficient detail to characterize the performance of each energy storage subsystem concept. Sixth, the conceptual energy storage subsystems were compared on each of the critical parameters. Seventh, a subsystem was selected for recommendation based on the results of the comparisons in step six above.

Since some of the conceptual energy storage subsystems had more than one option, the gathered data for each of these options was used for comparison along with secondary parameters of interest. Using this information energy storage subsystem options were selected for recommendations.

2.1.1.2 Requirements

The statement of work required a nominal ten kilowatt system capable of delivering 20 kilowatts to the load for 12 hours. A three phase, 208/120 volt, 60 Hz output was specified. System modularity was to be a consideration. The energy converter was specified to be one of the following three: wind turbine, solar photovoltaic, solar thermionic.

2.1.1.3 Establishment of Conceptual System Block Diagrams

Based on these requirements and some forecast use scenarios, the two block diagrams shown in Figures 2.1 and 2.2 were drawn. The only difference being that Conceptual System Configuration "A", Figure 2.1, uses a single diesel and/or commercial power backup to supply the entire load. Conceptual System Configuration "B", Figure 2.2, uses a diesel and/or commercial power to backup each module. The final choice would depend on the actual use scenario; however, it has very little, if any, impact on the choice of an energy storage subsystem.

If the energy converters are assumed to be modular (this assumption was used), there is an impact on the power system configuration. A single wind turbine could be used to generate the power in a form compatible with the load requirements; however, it would be extremely difficult to insure that two or more wind turbines could operate with uniform electrical output on an instantaneous basis. Identical voltage, phase, and phase rotation must be maintained at all times. This problem is not significant in the case of solar photovoltaic or thermionic systems since their output is direct current. In order to alleviate this problem with wind turbines, a direct current output was specified for them. This configuration

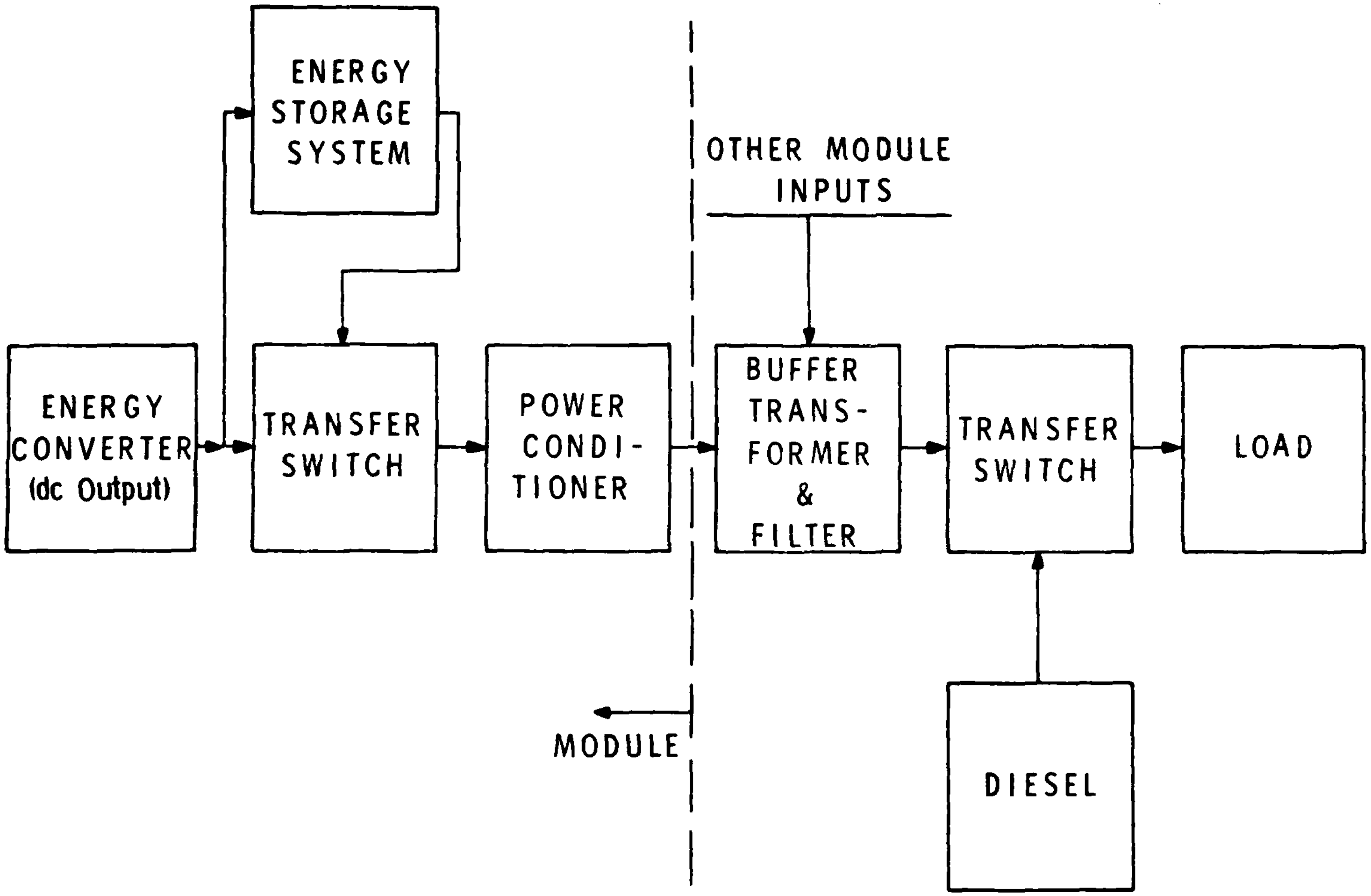


Figure 2.1 Conceptual System Configuration 'A' (Single Diesel Backup)

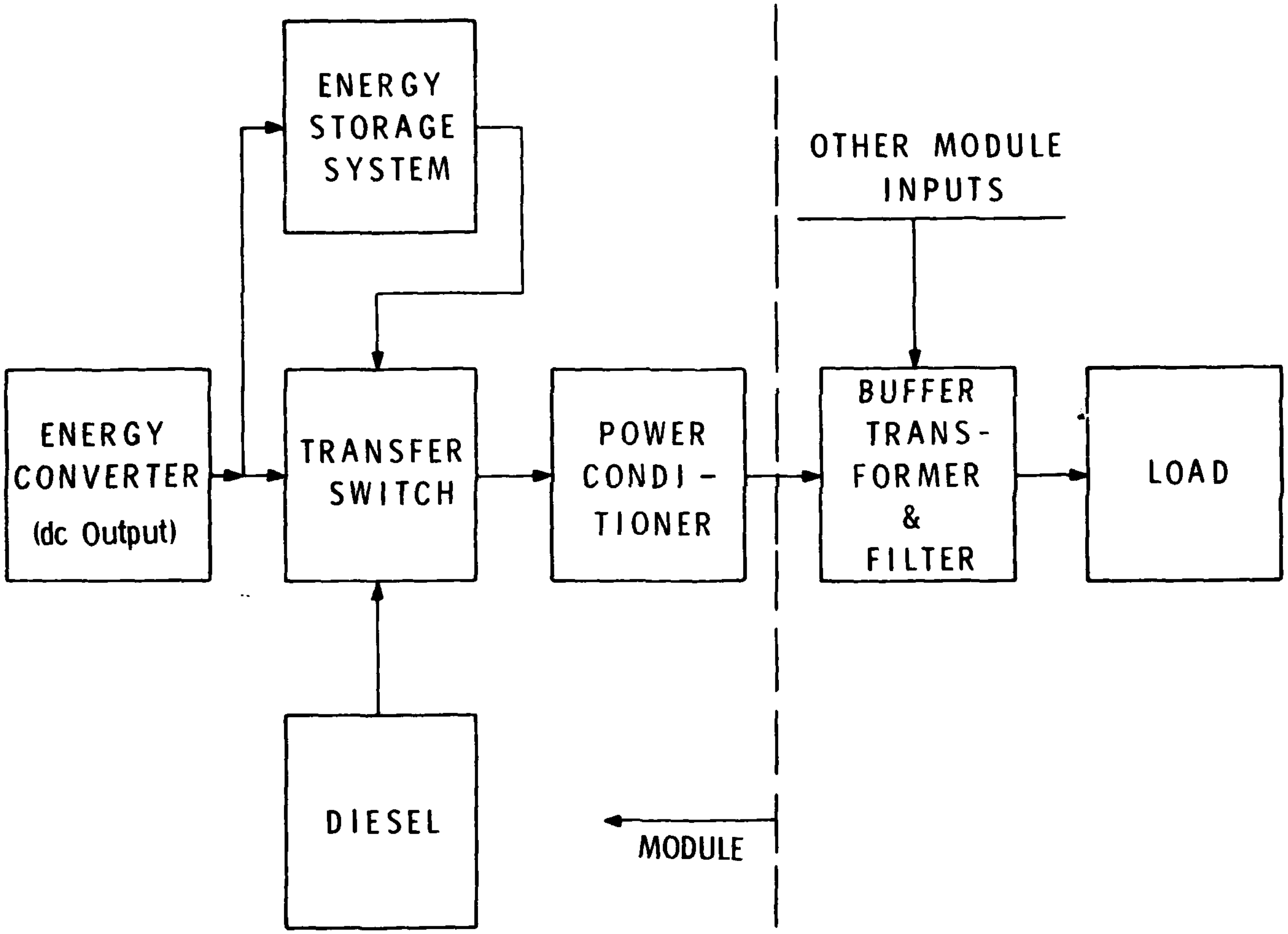


Figure 2.2 Conceptual System Configuration 'B' (Modular Diesel Backup)

required the use of an inverter to change the power back to alternating current with an accompanying efficiency penalty. However, this efficiency is usually high so the penalty is not severe. The power conditioning units are synchronized through a master control and interconnected, in parallel, through a buffer transformer/filter to the load.

2.1.1.4 Relationship Among Input Power, Output Power, and Stored Energy

Examination of the block diagrams gives a simple relationship between the input power, the output power, and power required to replenish the energy storage subsystem. The power output required from the energy converter, $P_{O_{EC}}$, is the sum of the load power, P_L, and the energy storage recharge power, P_{ES}.

$$P_{O_{EC}} = P_L + P_{ES} \tag{2.1}$$

The load power passes through the power conditioning unit or inverter; thus, the energy converter must supply the load power divided by the inverter efficiency.

$$P_L = \frac{\text{SPECIFICATION POWER OUTPUT}}{\text{INVERTER EFFICIENCY}} \tag{2.2}$$

The power required by the energy storage subsystem is somewhat more complicated since more factors affect it. Since the power also flows from the energy storage unit to the load through the inverter, the power delivered at the output of the energy storage subsystem is the specification power output divided by the inverter efficiency. The energy storage unit has a fixed size equal to the above value of specification power output divided by the inverter efficiency multiplied by the duration for power to be supplied by the energy storage system. This value is the total energy available from the storage system. The energy storage system has an efficiency of energy storage associated with it and division of the total available stored energy by the efficiency of energy storage yields the total energy input to the energy storage subsystem. Division of this total energy input by the time to recharge the energy storage system gives the energy storage recharge power, P_{ES}.

$$P_{ES} = \frac{\text{Specification Power Output x Specified Duration}}{\text{Inverter Efficiency x Energy Storage Efficiency x Recharge Time}} \quad (2.3)$$

The recharge time appears in the denominator of the P_{ES} term and short recharge periods (fast charge) increase this term and also the output from the energy converter. This, in turn, increases energy converter size, weight, and cost. On the other hand, some energy storage systems such as certain battery types need a specified minimum rate of charge which determines a maximum period for charging. These arguments have been presented to emphasize that the recharge time parameter selection can have a significant impact on total system size, weight, cost, and complexity. Therefore, the recharge period parameter should receive careful consideration in the specification. Another parameter which becomes a major factor in the above power equation is the efficiency of energy storage. This factor is important in comparison of candidate systems because of its impact on total system size, weight, and cost. Thus from a total system standpoint, a large, heavy, highly efficient energy storage subsystem may be more attractive than a small, lightweight inefficient subsystem.

2.1.1.5 Energy Storage Subsystem Candidates

The statement of work required investigation of hydrogen storage/heat engines, lead-acid batteries, nickel-hydrogen batteries, and advanced sulfur batteries as energy storage candidates. As a result of literature review and consideration of alternate energy storage methods the list of candidates was expanded to include: thermal storage/heat engine concepts; hydrogen storage/fuel cells; flywheels; nickel-cadmium and nickel-zinc batteries.

The candidate systems were grouped into five categories for comparison and selection. These categories were:

- Thermal Storage + Heat Engine
- Hydrogen + Heat Engine
- Hydrogen + Fuel Cell
- Batteries
- Flywheels

2.1.1.6 Discussion of Candidate Subsystems

The candidate energy storage subsystems were expanded into a more detailed block diagram which identified each major component or function. Data was gathered for the critical parameters for each component and then an aggregate number was developed for the total system. When a component such as a heat engine or generator was used in two different subsystems, the same values for each of the parameters were used to insure that the subsystems were compared on an equal basis. These results have been tabulated and discussed in Tables 2.1, 2.2, 2.3, 2.4, and 2.5. The numbers in parenthesis above each of the blocks in the block diagrams at the top of the tables are the totel energy and power level at that point. As an example, Table 2.1 summarizes the thermal energy storage and heat engine concept. The load requirement is 20 kilowatts for 12 hours or 240 hilowatt hours. This power must flow through an inverter which is approximately 80 percent efficient; therefore, it requires an input of 20/.8 or 25 kilowatts for 12 hours or 300 kilowatt hours. Similarly the heat engine drives a generator with typical efficiencies of 80 to 90 percent. For the worst case of efficiency the generator input would be about 31 kilowatts and 372 kilowatt hours. The heat engine input would be 103 kilowatts and 1.25 megawatt hours for an efficiency of 20 percent. The thermal storage unit has an energy efficiency of 90 to 95 percent and the total energy input required is 1.25/.9 or 1.315 megawatt hours. It was assumed in all calculations that the

TABLE 2.1

THERMAL ENERGY STORAGE & HEAT ENGINE, FOR 240 KW HR STORAGE

	(1315/8) kw hr/kw	(1250/103) kw hr/kw	(375/31) kw hr/kw	(300/25) kw hr/kw
INPUT FROM CONVERTER →	THERMAL STORAGE UNIT	HEAT ENGINE	GENERATOR	→ TO INVERTER
	Ref. 1	Ref. 2	Ref. 3	TOTAL
EFFICIENCY	.9 - .95	.2 - .3	.8 - .9	0.23
LIFE	>10 YR	5 YR	>10 YR	5 YR
EST. RELIABILITY	.998	.988	.9993	0.985
WEIGHT	40#/KWH	300#/KW	15 #/KW	63800#
VOLUME	.06 FT^3/KWH	7 FT^3/KW	.02 FT^3/KW	293/FT^3
EST. UNIT COST (K)	.004/KWH	5/KW	.5/KW	172.5

- TECHNOLOGY AVAILABLE - HARDWARE NOT AVAILABLE IN DEMONSTRATED SIZE
- RECHARGE TIME FROM 20 KW CONVERTER = 164 HRS.

TABLE 2.2

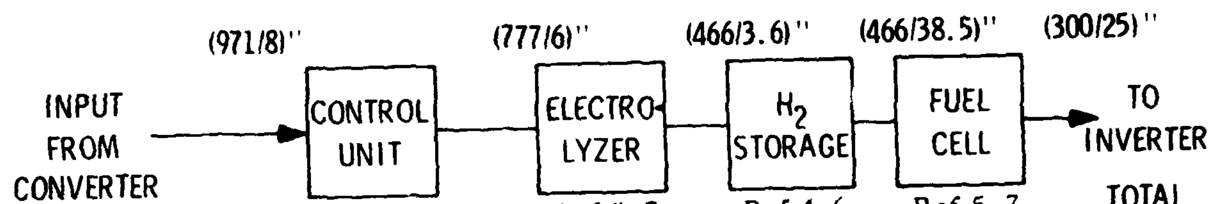
HYDROGEN ENERGY STORAGE & HEAT ENGINE FOR 240 KW HR

INPUT FROM CONVERTER →	CON-TROL UNIT	ELEC-TRO-LYZER	H_2 STOR-AGE	HEAT ENGINE	GENERA-TOR	→ TO INVERTER
	(2604/8)"	(2013/6)"	(1250/3.6)"	(1250/103)"	(375/31)"	(300/25)"
	Ref 3	Ref 5, 7	Ref 4, 6	Ref 2	Ref 3	TOTAL
EFFICENCY	.8 - .9	.6 - .9	1.00	.2 - .3	.8 - .9	.08 - 22
LIFE	>10 YR	10 YR	UNDEFINED ≈10 YR	5 YR	10-20 YR	5 YR
EST. RELIABILITY	.977	.865	.9996	.988	.99993	0.834
WEIGHT	25#/KW	30#/KW	5#/KWH	300#/KW	15#/KW	13,200#
VOLUME	$.5FT^3$/KW	$.5FT^3$/KW	$.008FT^3$/KWH	$7FT^3$/KW	$.02FT^3$/KWH	$190 FT^3$
EST. UNIT COST (K)	.5/KW	10/KW	.004/KWH	5/KW	.5/KW	148

- H_2O RECOVERY PROBLEM FROM EXHAUST OTHERWISE 1.25#/KWH OF H_2O IS REQUIRED TO FEED ELECTROLYZER
- HEAT ENGINE & H_2 STORAGE HARDWARE NOT AVAILABLE IN DESIRED SIZE
- O_2 VENTED
- RECHARGE TIME FROM 20KW CONVERTER = 326 HRS

TABLE 2.3

HYDROGEN ENERGY STORAGE & FUEL CELL FOR 240 KW HR STORAGE



	CONTROL UNIT (Ref 3)	ELECTROLYZER (Ref 5, 7)	H_2 STORAGE (Ref 4, 6)	FUEL CELL (Ref 5, 7)	TOTAL
EFFICIENCY	.8 - .9	.6 - .9	1.00	.6 - .65	.29 - .53
LIFE	>10 YR	10 YR	UNDEFINED ≈10 YR	10 YR	10 YR
EST. RELIABILITY	.977	.865	.9996	.865	.73
WEIGHT	25#/KW	30#/KW	5#/KWH	30#/KW	6000#
VOLUME	.5FT^3/KW	.5FT^3/KW	.008FT^3/KWH	.5FT^3/KW	25/FT^3
EST. UNIT COST (K)	.5/KW	10/KW	.004/KWH	30/KW	413

- REQUIRES H_2O RECOVERY
- O_2 VENTED
- H_2 STORAGE HARDWARE NOT AVAILABLE IN DESIRED SIZE
- RECHARGE TIME FROM 20 KW CONVERTER = 121 HRS

TABLE 2.4

BATTERY ENERGY STORAGE FOR 240 KW HR STORAGE

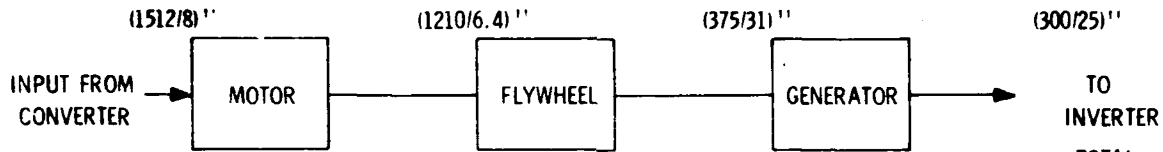
(469/8)" INPUT FROM CONVERTER → CHARGER → (375/6.4)" → BATTERY → (300/25) TO INVERTER

	CHARGER Ref 3	Ref 8, 10, 11, 12, 13, 14, 15 Near Term	Far Term Ref 8, 9, 16	TOTAL Near Term	TOTAL Far Term
EFFICIENCY	.8 - .9	7 - .85	.85 - .9	.56	.68
LIFE	10 YR	5 YR	>10 YR	5 YR	10 YR
EST. RELIABILITY	.977	.98	.98	.957	.957
WEIGHT	25#/KW	75#/KWH	12#/KWH	25000#	3800#
VOLUME	.5FT^3/KW	.4FT^3.KWH	.2FT^3/KWH	120/FT^3	7FT^3
EST. UNIT COST (K)	.5/KW	.15/KWH	.025/KWH	48	11

- HARDWARE AVAILABLE
- REQUIRE AMBIENT TEMP: +30^{0}F To 120^{0}F
- VENTED BATTERIES REQUIRE SOME AIR CHANGES
- RECHARGE TIME FROM 20KW CONVERTER = 59 HRS

TABLE 2.5

FLYWHEEL ENERGY STORAGE FOR 240 KW·HR STORAGE



	MOTOR Ref 2, 3	FLYWHEEL Ref 6, 7 Near Term	FLYWHEEL Ref 6, 7 Far Term	GENERATOR Ref 2, 3	TOTAL Near Term	TOTAL Far Term
EFFICIENCY	.8 - .9	.31	.69	.8 - .9	.2	.56
LIFE	10 YR	1 YR	2 YR	> 10 YR	1 YR	2 YR
EST. RELIABILITY	.997	.975	.975	.997	.97	.97
WEIGHT	15#/KW	150#/KWH	20#/KWH	15#/KW	57000#	8000#
VOLUME	0.2 FT^3/KW	.25 FT^3/KWH	.25 FT^3/KWH	.02 FT^3/KW	95 FT^3	95 FT^3
EST. UNIT COST (K)	.5/KW	.1/KWH	.4/KWH	.5/KW	54	166

- TECHNOLOGY AVAILABLE HARDWARE NOT AVAILABLE IN PROPER SIZE
- REQUIRES BEARING REPLACEMENT ANNUALLY
- EFFICIENCY OF FLYWHEEL = $\frac{\text{POWER OUTPUT}}{\text{POWER OUTPUT} + (T_C + T_D)\text{ AVG BEARING LOSS}}$ (2.4)
- RECHARGE TIME FROM 20KW CONVERTER + 189 HRS

energy converter supplied 20 kilowatts of output and that the load was at the nominal level of 10 kilowatts. The power from the energy converter for the load is 10 kilowatts divided by the inverter efficiency, 80 percent, or 12.5 kilowatts. The remaining excess power available from the converter output, 7.5 kilowatts, was available for recharging the energy storage subsystem. The value of 7.5 kilowatts was rounded off to a value of 8 kilowatts which was used in the calculations.

2.1.1.6.1 Thermal energy storage and heat engine

The thermal energy storage and heat engine subsystem is shown in Table 2.1 and consists of a thermal energy storage unit, a heat engine to convert the stored heat back to mechanical energy, and a generator to convert the mechanical energy back to electrical energy. Other concepts such as thermionic and thermoelectric converters could have been used, but their efficiency was below that of the heat engine and generator combination. This subsystem concept, because of the low heat engine efficiency, requires a large amount of stored energy and requires a rather long time to recharge a fully depleted subsystem. The cost of the heat engine is a major cost driver. The necessary technology is available to build the system, however, demonstrated hardware is not available in the required size range. This subsystem could be a very attractive candidate for a fully integrated shelter heating and electrical power system.

2.1.1.6.2 Hydrogen energy storage and heat engine

The concept of making and storing hydrogen seems attractive on the surface; however, it has many disadvantages when used in relatively small remote site power systems. A conceptual storage unit is shown in Table 2.2. In order to make the hydrogen an electrolysis unit is presently the optimum method and the efficiency of these devices is typically 60 to 65 percent, however, values of up to 90 percent have been reported.[7] Furthermore, these units require reasonably well regulated power input which necessitates the use of an input power conditioning and control unit similar to a battery charger. This concept also suffers from the low efficiency and high projected cost for the heat engine. Due to the poor overall efficiency, a long recharge period is required. The hydrogen storage technology is a changing field and mature hardware is not currently available. The electrolyzer unit is also relatively expensive and requires water to make hydrogen. The water must be supplied, similar to fuel for a diesel, or recovered from the exhaust of the heat engine. Recovery of the water vapor in appreciable amounts from the exhaust does not seem practical at this time.

2.1.1.6.3 Hydrogen energy storage and fuel cell

This concept is shown in Table 2.3 and is the same as the previous example except that the heat engine and generator have been replaced by a fuel cell which converts hydrogen and oxygen into water with the direct production of electricity. The advantages of this concept are improved efficiency and ease of recovering the exhaust water. The chief disadvantages are high cost and a moderately long recharge time.

2.1.1.6.4 Battery energy storage

This conceptual subsystem is shown in Table 2.4 and is probably the most mature technology of all the concepts. The subsystem consists of a battery and a charger to regulate the incoming power from the energy converter. This concept offers a high overall efficiency and low cost. It has, due to the high efficiency, the shortest recharge time for a fully depleted storage system. The batteries do require a moderate operating temperature range and, if of the vented type, air charges are necessary in the compartment containing them to prevent accumulation of explosive gas.

2.1.1.6.5 Flywheel energy storage

Some references[6,7] have indicated that flywheel or energy wheel subsystems such as the one shown in Table 2.5

are a competitive energy storage subsystem for applications such as those being studied here. This may be true if the anticipated performance levels are achieved, however, the efficiency of the wheel is inversely proportional to the sum of the charge and discharge times. For applications such as the one being studied the charge and discharge times are relatively long and reduce the efficiency to a relatively low level. In order to achieve the higher efficiencies for the future projections more expensive materials such as fused quartz will be used. State of the art wheels are steel and the ball bearings require annual replacement. Lubricant for the bearings is an important consideration, particularly in the ambient or environment of concern to the Air Force.

2.1.1.7 Comparison of the Candidate Subsystems and Recommendation of a Subsystem

The total energy storage subsystem performance parameters are tabulated in Table 2.6 for comparison. The performance parameters have been assigned a relative value of 1 to 7 for each of the subsystems considered plus a parameter of availability has been added. These relative values have been tabulated in Table 2.7 and were used to aid in selecting a subsystem for recommendation. Examination of the totals indicates that near and far term batteries have the lowest scores and thus the best relative ranking of the conceptual subsystems studied. The near term batteries are recommended for this application even though the far term batteries have a lower relative score. The far term batteries are not really available and their projected performance is being compared with hard experimental data for near term batteries. When the advanced batteries become available they could be substituted into the subsystems for the near term batteries.

2.1.1.8 Comparison of Battery Options

The battery types considered are given in Table 2.8 and relative comparison is made in Table 2.9. It can be seen that the Lithium/Aluminum-Iron Sulfide and Sodium-Sulfur batteries have the

TABLE 2.6

COMPARISON OF ENERGY STORAGE SYSTEMS

	THERMAL & HEAT ENGINE	HYDROGEN + HEAT ENGINE	HYDROGEN + FUEL CELL	BATTERY (Near Term)	BATTERY (Far Term)	FLYWHEEL (Near Term)	FLYWHEEL (Far Term)
EFFICIENCY	.23	.12	.31	.63	.68	.2	.56
LIFE (YR)	5	5	10	5	10	1	2
EST. RELIABILITY	.985	.834	.73	.957	.957	.97	.97
WEIGHT (#)*	63,800	13,200	6,000	25,000	3,800	57,000	8,000
VOLUME (FT^3)*	293	190	25	120	7	95	95
EST. COST (K)* PER UNIT	172.5	148	413	48	11	54	166
RECHARGE TIME (HRS)**	164	326	121	59	55	189	67

* FOR AN ENERGY STORAGE SYSTEM WHICH DELIVERS 240 KWH @ 20KW TO THE LOAD.

** FOR A FULLY DISCHARGED ENERGY STORAGE SYSTEM, 20 KW CONVERTER OUTPUT WITH 10 KW DELIVERED TO LOAD.

TABLE 2.7

RELATIVE RANKING OF CANDIDATE SUBSYSTEMS

	Thermal & Heat Engine	H_2 + Heat Engine	H_2 + Fuel Cell	Battery (near term)	Battery (far term)	Flywheel (near term)	Flywheel (far term)
Efficiency	5	7	4	2	1	6	3
Life	3	5	1	4	2	7	6
Est. Reliability	1	6	7	4	5	2	3
Weight	7	4	2	5	1	6	3
Volume	7	6	2	5	1	3	4
Est. Unit Cost	6	4	7	2	1	3	5
Recharge Time	5	7	4	2	1	6	3
Availability	4	5	3	1	7	2	6
TOTALS	38	44	30	25	19	35	33

Based on relative values 1 through 7

TABLE 2.8

BATTERY TYPES

BATTERY TYPE	HARDWARE AVAILABILITY DATE	COST ($/kwh)	EFFICIENCY (%)	WEIGHT (#/kwh)	VOLUME (ft^3/kwh)	LIFE YEARS	LIFE CYCLES
LEAD ACID							
VENTED (SOTA)	1978	58	82	115	.8	5	300
(IMPROVED)	1979	54	80	110	.7	5	400
SEALED	1980	150	85	75	.4	5	700
NICKEL CADMIUM							
VENTED (POCKET PLATE)	1978	300	75	90	.9	20	2000
(SINTERED PLATE)	1979	300	75	70	.3	20	2000
SEALED	1979	400	75	55	.3	10	1000
NICKEL HYDROGEN	1981	400	70	21	.5	10	1000
NICKEL ZINC	1981	100	78	28	.2	5	500
LITHIUM/ALUMINUM-IRON SULFIDE	1985	25	85	15	.12	15	1500
SODIUM - SULFUR	1987	28	90	8	.2	15	4000

TABLE 2.9

RELATIVE RANKING OF BATTERY OPTIONS

Battery Type	Availability	Cost	Efficiency	Weight	Volume	Life	Total
Lead Acid							
Vented (sota)	2	4	4	10	9	8	37
(imp)	5	3	5	9	8	9	39
Sealed	6	6	2	7	6	7	34
NiCd							
Vented (pocket)	1	7	8	8	10	1	35
(sintered)	3	8	7	6	5	2	31
Sealed	4	9	9	5	4	6	37
$Ni-H_2$	8	10	10	3	7	5	43
Ni-Zn	7	5	6	4	3	10	35
$LiAl-FeS_2$	9	1	3	2	1	4	20
Na-S	10	2	1	1	2	3	19

best relative ranking, however, demonstrated hardware is not presently available. The lead-acid, nickel-cadmium, and nickel-zinc types are grouped tightly in the relative rankings. The vented type of batteries have a disadvantage for remote site use in cold areas because the batteries must be maintained at a moderate temperature, yet fresh air must be circulated through the battery compartment. If outside air is at very low temperatures, -40°F, and the battery compartment is to be maintained at +60°F, the heating requirement for this air could be significant. A portion of this required heat might be picked up from the charger and inverter inefficiency in the final system design. The nickel batteries have one other disadvantage which is that the charge rate must be relatively high, 10 to 15 hours. This disadvantage can be overcome to a great extent by dividing the total battery into sections and charging each section sequentially.

Based on the data from Tables 2.8 and 2.9 the use of sealed lead-acid batteries is recommended because they have a good relative rating, are available in the near future, and reduce the compartment ventilation problem. All of the other types except nickel cadmium and nickel hydrogen are under active investigation by the Department of Energy and others. A secondary choice is the nickel-zinc battery as a lightweight, low volume option.

2.1.2 Wind Power Systems

2.1.2.1 Characteristics, Availability, and Approximate Cost

Representative wind power systems available as energy sources for remote site applications have been examined and are tabulated according to availability (see Table 2.10). Most of the work in this effort was concerned with the category "available within 5 years". A survey of the programs aimed at yielding devices for wind power electricity generation in the 5 to 10 years and the over 10 year time frames has also been conducted.

TABLE 2.10

POWER SYSTEMS AVAILABLE

Energy Converter	Energy Form	Availability Yrs
Wind Turbine Grumman 8kw	AC	0-5
Wind Turbine United Technology Crop. 8kw	AC/DC	0-5
Wind Turbine Electro WVG50G 6kw 3Ø	AC	0-5
Wind Turbine Jacobs J-47 3kw 120v	DC	0-5
Wind Turbine Wind Power Systems, Inc. 8kw	AC	0-5
Darrieus Wind Turbine Alcoa Corp. 8kw	AC	0-5
Darrieus Wind Turbine Dynergy Corp. 4 Unit Stack 5 kw	AC	0-5
Wind Turbine Windworks Inc. 8kw	AC/DC	0-5
Cyclogyro-Gyromill McDonnell Douglas	AC	5-10
Diffuser Augmenter Wind Turbine Grumman Aerospace Corp.	AC	5-10
Vortex Augmenter Wind Turbine Polytech Inst of New York	AC	5-10
Dynamic Inducer Wind Turbine Aeroenvironment Inc.	AC	Over 10
Tornado Wind Turbine Grumman Aerospace Corp.	AC	Over 10
Electro Fluid-Dynamics (EFD) Generator University of Dayton	High Voltage DC	Over 10
EFD Generator Marks Polarized Corp.	High Voltage DC	Over 10
Madaras Rotor University of Dayton	AC	Over 10
Lift Translator University of Texas	AC	Over 10

The emerging family of 8 kilowatt, high reliability wind turbines is of special interest for remote site application[17] because of the emphasis on reliable operation. In addition, the rated output of 8 kilowatts makes this an attractive power source for an energy storage and supply module supplying 4 or 5 kilowatts of power to a load. Manufacturers estimated average yearly output in kilowatt hours per year per square foot of frontal/disc area at average wind speeds from 5 miles per hour through 25 miles per hour is tabulated for four candiate 8 KW wind turbine generators on the left side of Table 2.11. Instantaneous output and efficiencies are tabulated at instantaneous windspeeds from 5 miles per hour to 25 miles per hour on the right side of Table 2.11. Available power is calculated assuming a cylindrical or rectangular volume of air the size of the disc for a horizontal axis turbine or the frontal area for a vertical axis turbine, and isentropically reducing the velocity to zero.

$$F = \int_V^o \dot{m} dV = \rho A V^2 \tag{2.5}$$

A = frontal/disc area

$\dot{m}$ = mass flow rate

V = velocity of wind

ρ = air density

where F is the force due to the time rate of change of momentum of the wind.

$$HP_{avail} = \frac{FV}{550} \tag{2.6}$$

where HP_{avail} is the available power of the wind.

The 8 KW high reliability wind power systems manufacturers are listed below:

- Wind Power Systems, Inc. of San Diego, California.[18] This downwind system features flexible fiberglass rotor blades flexing in the flat direction to relieve bending moments due to gusts. The blade structure is single shell with foam core. The prototype was installed in the spring of 1978 at a test site near San Diego, California where

TABLE 2.11

PREDICTED PERFORMANCE OF HIGH RELIABILITY 8 KW WIND TURBINE GENERATORS

Wind Turbine frontal/disc area	Average Windspeed mph	Manuf. est. Output kwhr/yr/ft^2	Manuf. est. Average Output watts/ft^2	Instantaneous Windspeed mph	Available Power watts/ft^2	Instantaneous Output watts/ft^2	Instantaneous Output kw	Eff %
A 850 ft^2	5	0	0	5	1.27	0	0	0
	10	18.82	2.14	10	10.18	1.41	1.2	13.9
	15	36.47	4.16	15	34.34	4.70	4.0	13.7
	20	56.47	6.45	20	81.40	9.41	8.0	11.6
	25	56.47	6.45	25	159.00	9.41	8.0	5.9
B 755 ft^2	5	1.32	0.15	5	1.27	0	0	0
	10	30.46	3.44	10	10.18	1.32	1.0	13.0
	15	60.92	6.95	15	34.34	7.95	6.0	23.1
	20	74.17	8.46	20	81.40	15.23	11.5	18.7
	25	75.50	8.61	25	159.00	27.81	21.0	17.5
C 1350 ft^2	5	0.63	0.07	5	1.27	0	0	0
	10	10.0	1.14	10	10.18	0	0	0
	15	38.89	4.44	15	34.34	1.93	2.6	5.6
	20	88.89	10.15	20	81.40	6.15	8.3	7.6
	25	166.67	19.02	25	159.00	14.07	19.0	8.9
D 804.25 ft^2	5	0	0	5	1.27	0	0	0
	10	19.62	2.30	10	10.18	1.12	0.9	11.0
	15	22.45	2.56	15	34.34	5.22	4.2	15.2
	20	86.32	10.11	20	81.40	12.43	10.0	15.3
	25	94.59	11.07	25	159.00	19.27	15.5	12.1

maximum winds are 50-55 mph. Initial testing used a DC generator with future plans to test an induction generator. Funding is provided by a U.S. Navy Civil Engineering Contract. Tests are planned at the Rocky Flatts, Colorado test site starting in the summer of 1979.

- United Technology Inc. of East Hartford, Connecticut.[19] The bearingless rotor concept used on the Sikorsky helicopter tail rotor is projected for use in this system. The composite material of the rotor deforms in torsion to govern speed, consequently, no bearings are required to change pitch on the rotor blades. Prototype testing is scheduled at the plant in the spring of 1979 and then testing is to be transferred with the prototype unit to Rocky Flats, Colorado. Plans are to test both AC induction and DC generator units. Funding is under a DOE contract.

- Alcoa Inc. of Alcoa Center, Pennsylvania.[20] Alcoa is developing several Darrieus vertical axis turbines. The 8 KW is 45 ft high and 30 ft in diameter and is to be fabricated by Stolle Engineering Co. of Sidney, Ohio. Testing of several wind turbines, including the 8 KW, is anticipated during the winter of 1979-1980 at both the plant in Alcoa Center, Pennsylvania and at Rocky Flats, Colorado. Funding is under a DOE contract.

- Grumman Inc. Ronkonkoma, New York.[21] A prototype is expected to be ready for testing during the fall of 1979. The 8 KW machine under construction incorporates lessons learned from an earlier 15 KW Grumman wind turbine generator. Funding is under a DOE contract.

- Windworks, Inc. of Mukwonago, Wisconsin.[22] Windworks have completed about half of a 2-1/2 year DOE contract to produce a high reliability nominal 8 KW wind turbine. The rotor is 3 bladed downwind 30 ft diameter and preliminary predicted performance of the generator appears to be similar to other 8 KW high reliability machines. Hardware is anticipated suitable for remote site application in less than two years. Testing is anticipated at the Rocky Flats, Colorado test site during the winter of 1979-1980.

Table 2.12 shows estimated unit dollar costs in 1978 dollars for two cases: (1) one prototype unit, and (2) one production unit in quantities of 100 units. These costs include only the energy converter and does not include processing or storage equipment.

2.1.3 Advanced Wind Energy Converters

2.1.3.1 Cyclogyro

The Cyclogyro is a vertical axis turbine with straight, variable pitch blades. Several advantages are claimed over the Darrieus vertical axis machine. The Cyclogyro is a self started and controlling the pitch permits extracting more power from the air by operating near max L/D for the blades yielding higher efficiency. In addition straight cyclogyro blades are cheaper to manufacture than curved Darrieus turbine blades. Pinson Energy Corp., Marston Hills, Mass. manufactures a Cycloturbine 12 ft in diameter with three straight 8 ft blades. Output is 4 KW at 30 mph wind and 2 KW at 24 mph wind. A 1 KW version is under development by Pinson and Aerospace Systems, Inc. of Burlington, Mass.[23]

2.1.3.2 Diffuser Augmented Wind Turbine (DAWT)

The DAWT is a ducted fan expanding the flow aft of the fan. Flow separation on the inner walls of the diffuser is a major problem. Grumman Aerospace Corp., Bethpage, Long Island is treating this problem with a combination of slots to introduce high energy air to the boundary layer and careful attention to divergence angles and smoothness. Grumman states the first generation DAWT could provide approximately twice the power of a wind turbine without the duct considering the same turbine diameter and wind. Grumman estimates that the cost of the DAWT could be up to 50% cheaper than conventional wind turbines for the same rated power.[24] A major challenge is designing a duct structure that will withstand strong winds, retain a blade in case of failure, and keep system costs competitive.

TABLE 2.12

TYPICAL UNIT COST (THOUSANDS) HIGH RELIABILITY
8KW WIND TURBINE GENERATORS

WIND TURBINE	PROTOTYPE (1 UNIT)	PRODUCTION (1 UNIT) (IN QUANTITIES OF 100 UNITS)
1	30	20-25
2	75-100	15-20
3	20-30	12
4	13	10

2.1.3.3 Vortex Augmenter Wind Turbine

The vortex augmenter places two fans aft and near the leading edge of a delta wing at a positive angle of attack. The fans are placed in regions of high vorticity thus augmenting the effect of the wind on the fans. Sforza, Polytechnic Institute of New York, Farmingdale, has completed a model 18 ft long, 10 ft wide with two 3 ft diameter rotors. Wind speed seen by the rotors can be varied by varying the angle of attack or actuating the trailing edge flaps. Sforza estimates nearly doubling effective wind velocity with this approach.[23]

2.1.3.4 Dynamic Inducer Wind Turbine

The dynamic inducer employs end plates on the fan blades to reduce spanwise flow and resulting losses from shed tip vortices. Lissaman, Vice President of AeroVironment Inc., Pasadena, California, and co-designer of the Gossamer Condor, man powered aircraft, is pursuing this concept. Drag produced by the end plates and structural loads in unsteady wind conditions are problems with the dynamic inducer. Lissaman says, "We have not proved the concept practical, but we are hopeful."[23]

2.1.3.5 Tornado Wind Turbine

The Tornado is a vertical axis turbine with operable vertical vents. The vents facing the wind open and the downwind vents close causing a large vortex to form and at the top of the turbine. Meanwhile the low pressure in the center of the vortex draws high velocity air in the bottom of the turbine driving a small rotor located near the bottom of the tower. To use this approach it is necessary to build a large tower with a small rotor inside. Grumman Aerospace Corp., Bethpage, New York is doing wind tunnel tests which indicate augmentation ratios as high as 1000 are possible.[23]

2.1.3.6 Electro Fluid Dynamics (EFD)

In an EFD generator the wind moves charged water droplets through an electrostatic field to a collector accomplishing work in a manner similar to that of a wire being moved through a magnetic field in a conventional generator. Making charged water droplets is the area of research concentration at this time. The University of Dayton is using liquid nitrogen to cool moist air to produce small liquid droplets that can be charged in a corona discharge.[25] Marks Polarized Corp., Whitestone, New York is trying to improve efficiency by projecting small water jets through an electric field to charge the droplets.[23] The EFD generator has no moving parts and has produced over 50,000 volts using air in a choked nozzle in experiments at Aeronautical Research Laboratories, Wright-Patterson Air Force Base, Ohio, in the late 1960's and early 1970's.[25]

2.1.3.7 Madaras Rotor

Julius Madaras invented the concept in the 1920's using a rotating cylinder to produce lift in a uniform stream. The system consists of a circular track with a train of flatcars. Each car has an electrically driven vertical rotating cylinder mounted on it. The wind provides the uniform stream which induces a horizontal lift force to propel the car on the track. Power is extracted from generators driven by the wheels of the train and transmitted on a third rail operating like a reversible electric train.

2.1.3.8 Lift Translator

The lift translator can be likened to a cyclogyro vertical axis wind turbine laid on its side. The idea can be adapted to wind or water power. Most of the current DOE funding is to develop a water activated system.

For wind application the apparatus consists of airfoils attached to an endless belt at an angle of attack such that on one side of the belt they are pushed up by the wind while on the other side of the belt they are pushed down. A 45 ft high working model constructed at the University of Texas at Dallas proved operational feasibility of the concept. The operational model reportedly generated up to 15 KW of power and was terminated after nine months of operation. The challenge now is cost competition with other advanced concepts.[23]

2.1.3.9 Summary

A number of variations of advanced wind energy converter concepts are being pursued through test and experimentation. Some like the DAWT and the EFD generator hold considerable promise but most are at least five years or more from completion of successful prototype testing.

2.1.4 Solar Photovoltaic Energy Conversion System

2.1.4.1 Introduction

Direct energy conversion devices which use semiconductor materials to produce electrical power by subjecting the material to electromagnetic radiation are called radiation-voltaic-energy conversion devices. Both thermal sources and light sources are used presently in research dealing with this energy converter.

Photovoltaic conversion is one of eight solar energy technologies being developed by DOE. These techniques were viewed by DOE as viable alternatives for providing substantial energy to the nation. Photovoltaic cells or solar cells directly convert electromagnetic radiation to electricity. The primary energy source for photovoltaic cells, at present, is energy from the sun hence the name solar cell. The major advantages of solar photovoltaic energy conversion are:

1. direct conversion of sunlight into electricity
2. solar cells are not limited by Carnot efficiency
3. severe thermal problems may be avoided
4. inherent ability to utilize both[26] specular radiation and diffuse radiation

5. least affected by "economics-of-scale"[27]
6. potential utilization of existing structures
7. simple operation and maintenance
8. modular design of photovoltaic arrays allow replacements of and additions to systems without incurring downtime of entire system.

Solar photovoltaic conversion systems were first used and are still being used extensively in the U.S. space program; these systems currently have a maximum capacity of 10 KW. The major requirements of the space systems have been high efficiency, low-weight, and radiation tolerance. The major disadvantage of solar photovoltaic cells is high cost. The cost of silicon solar arrays can vary from $12,000 to $30,000 per peak kw, depending on the quantity of arrays purchased.[28] The high cost is attributed to the low production of terrestrial solar photovoltaic panels. For example, the total market[29] in 1976 was estimated by DOE to be 300 peak KW_e. Current programs by DOE are aimed at production of low cost polycrystalline silicon material. Expansion of photovoltaic applications will occur when the technology matures and system costs are reduced.

Another interesting approach to reduce the cost of solar arrays involves the design of a photovoltaic concentrating array[30] which uses optical means to concentrate sunlight on silicon solar cells. The purpose of the photovoltaic concentrating array development was to reduce the number of relatively high priced solar cells through the use of lower cost lenses. The concentrating array operates at a concentration ratio of 40, tracks the sun in two axes and is passively cooled. Other types of concentrating lenses and mirrors are being investigated at present.

2.1.4.2 Basic Operating Principles

Solar photovoltaic energy systems provide a simple clean method for direct conversion of sunlight to electrical power. These systems require no complex machinery, heat engine cycle, or intermediate conversion to heat. Since they are intrinsically modular, photovoltaic systems are potentially cost effective on a small scale.

A solar cell is formed when a semiconductor material that supplies extra electrons (called "n-type") is joined to a semiconductor material deficient in valence electrons (called "p-type"). These two types of semiconductors are formed by adding small amounts of impurities, called dopants, to a semiconductor material.

In a semiconductor, the conduction band is separated from the valence band by an appropriate energy gap, so that electrons occupying the upper energy levels of the valence band can be optically excited to the lower levels of the conduction band.[6] A quantum of light, called a photon, carries energy which is proportional to its frequency, and inversely proportional to its wavelength. A photon of sufficient energy can excite an electron from near the top of the valence band into energy levels near the bottom of the conduction band.

When a photon strikes a p-n junction, electrons (current) are caused to flow through the load. Large numbers of "holes" (valence electron deficiency) flow from the p-region to the n-region, and a large electron flow occurs in the opposite direction. To achieve a high conversion efficiency it is desirable to produce electron-hole pairs within a very short distance of the p-n junction. The p-n junction is a built in potential gradient which separates the electrons and holes.

Solar cells are the basic unit of a photovoltaic power system. To achieve higher power levels, individual cells are combined in series to form a module. Modules are then grouped to form an array. Arrays of photovoltaic cells can be connected in series and parallel to adjust the voltage and current to satisfy energy and reliability requirements. The energy conversion devices can be coupled with an energy storage system to compensate for the day-night cycle and cloudy weather conditions. Also, the current produced by the photovoltaic device is direct current, requireing an inverter to produce AC current.

2.1.4.3 Current Solar Photovoltaic Applications and Projected Trends

Previously solar cell applications were limited to deserts, mountain peaks, and other remote areas for use in forest lookouts, meterological stations, and irrigation systems as well as the space program. With the rising costs of fuel, along with the increase in shortages of fuel, especially during the winter months, there is a rapidly increasing utilization of solar energy. Already there are solar houses, solar libraries, and others are adding solar systems in conjunction with existing systems. The world's largest terrestrial photovoltaic installation is at Mississippi County Community College. It features a fuel-free environment using a solar array to generate all of its electricity and the heat from the array for heating water and space.

High costs, limited demand, and current low industry capacity form an internally reinforcing set of conditions in opposition to widespread use of this technology. Presently, there are two manufacturers of single-crystal silicon solar arrays and two pilot production lines for cadmium sulfide (CdS) arrays.

The Photovoltaic Program, under the direction of the U. S. Department of Energy, is striving to expand the commercial use of photovoltaic systems as rapidly as possible. The overall objective of the program is to ensure that photovoltaic conversion systems play a significant role in supplying energy to the nation by the year 2000.

Near term goals include array prices $1-2/peak watt at an annual production rate of 20 peak megaWatts in 1982; mid-term forecasts prices $0.50/peak watt, and an annual production rate of 500 peak megaWatts in 1986. Far term goals include prices $0.10 to $0.30 per peak watt in 1990, and an annual production rate of 50 peak GWe in the year 2000. At this price range, photovoltaic systems should be cost effective for widespread utility applications.[28,29]

2.1.5 Solar Thermionic Power

Thermionic energy conversion is an attractive method for converting solar thermal energy directly to electricity without use of moving parts or high pressures in the conversion process. The process is simple and environmentally clean. Heat energy from the sun heats a metal electrode (the hot emitter) which boils off electrons from the surface. The emitted electrons cross a narrow interelectrode gap and condense on the collector. In this manner a flow of electrons is established which can be used to provide power to a load.[31]

A variety of thermionic converters have been developed using solar, nuclear, and fossil fuel sources. A large effort has concentrated on developing converters for use with nuclear reactor heat sources to be used in space power systems. Currently another large effort is directed toward thermionic topping cycles in coal fired central station power plants.[33]

A thermionic converter (LC-9) built by General Atomic for NASA as part of the in core nuclear space reactor program is the record holder for converter life. The LC-9 operated with stable performance for over five years at an emitter temperature of 1970°K.[32]

While the tendency for long life with no moving parts is an impressive advantage for using solar heated thermionic converters to provide electrical energy, more information needs to be gathered on the effects of thermal cycling on thermionic converter life. A solar thermionic converter is exposed to the thermal cycling process when the sun comes up and when the sun goes down plus cycling due to changes in cloud cover during the day. Converter materials and fabrication techniques that will endure large numbers of thermal cycles are areas for investigation.

In the thermionic conversion process heat is rejected at over 1000°K. This represents a large energy loss bringing the conversion system efficiency down to around 15%. If a bottoming cycle, such as a steam or other fluid cycle, can be added to utilize the rejected heat[32] another 30% efficiency can be obtained bringing the overall system efficiency up to about 45%. Such a concept would increase the attractiveness of a thermal energy storage system.

Eleven organizations are working in five areas to improve thermionic converter performance. Figure 2.3 is a program chart showing the relationship of these activities. As a result of these research activities an increase in thermionic converter efficiency from the current 15% to around 25% is expected in the 1985 time period.[34]

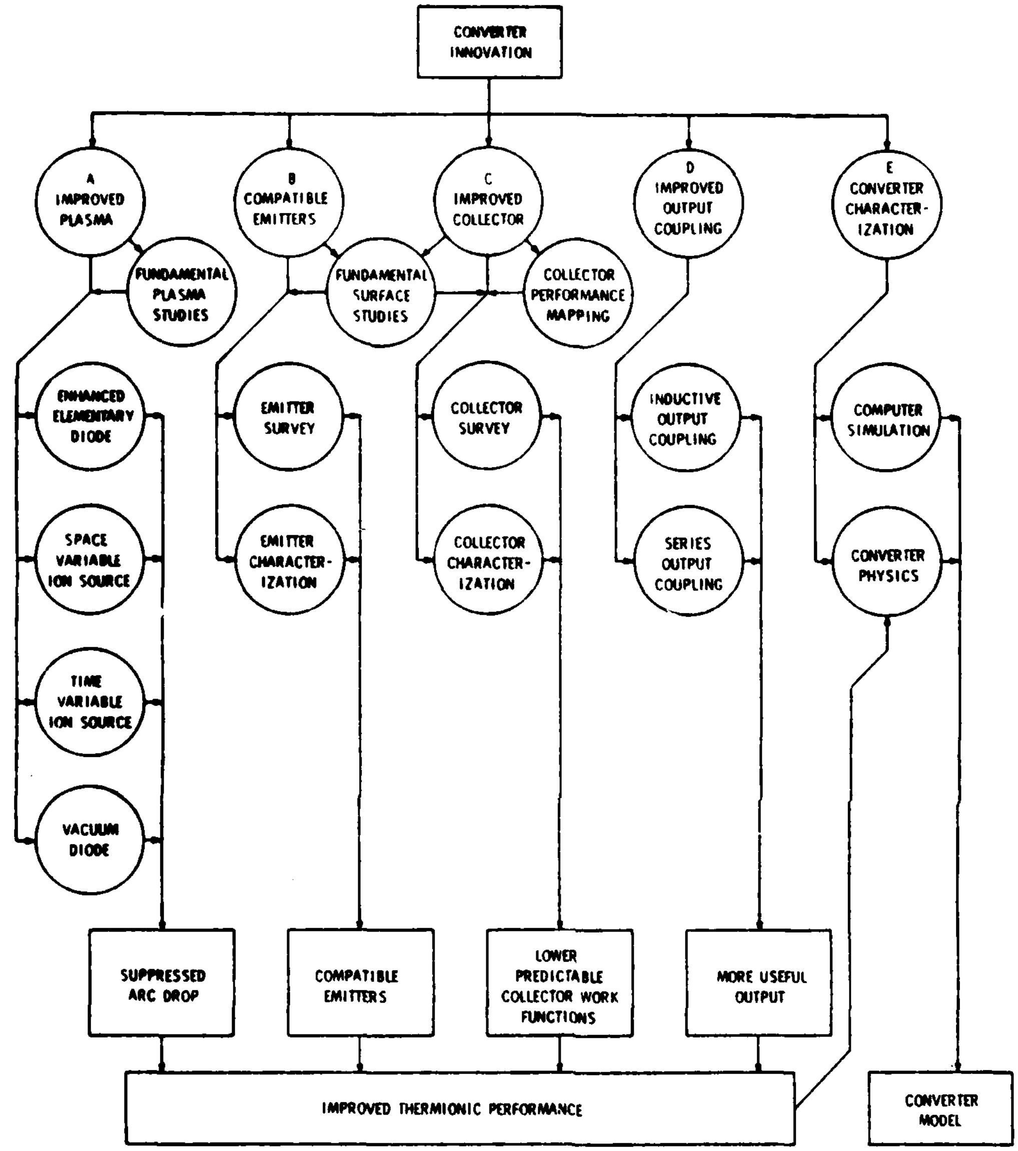
The Jet Propulsion Laboratory performed a comprehensive investigation of the application of solar thermionics to terrestrial applications in 1975.[35] One of the objectives of the study was to provide a cost estimate of a complete solar thermionic power system unit-module utilizing mass production techniques. The JPL cost estimate on a basis of 20 KWe is $2,400 per KWe for a 20 KWe, 28 v converter. For the complete solar thermionic power system plant the cost is $40,000 per KWe for a 20 KWe plant. Costs are given in 1975 dollars.

Since thermionic converters operate in a partial vacuum without moving parts and are modular, they are particularly adaptable to solar application at remote sites. The high temperature, high power density characteristics provide an excellent match to the operating characteristics of a solar receiver.[33]

2.1.6 Converter Comparison and Recommendations

2.1.6.1 Converter System Size Considerations

Size considerations for wind turbines can be discussed in terms of disc area or frontal area for a given KW rating. To compare thermionic and photovoltaic sizes for a nominal 5 KW continuous load, Bethel, Alaska in May yields about 7 hours of sunlight per day and was selected (see Table 2.13). This is the best time of the year at this



CONTRACTOR	CURRENT ACTIVITIES				
	A	B	C	D	E
Ames Research Center		X	X		
Arizona State University		X			
Jet Propulsion Laboratory	X	X	X		
Lewis Research Center		X	X		X
Los Alamos Scientific Laboratory		X			
Naval Research Laboratory		X	X		
Oregon Graduate Center		X	X		
Rasor Associates Incorporated	X	X	X	X	X
State University of N.Y. (Buffalo)	X				X
Thermo Electron Corporation	X	X	X	X	X
University of Minnesota	X				

Figure 2.3 Thermionic Converter Research [31]

TABLE 2.13

CONVERTER SYSTEM SIZE CONSIDERATIONS

	HORIZONTAL AXIS	VERTICAL AXIS	DISC AREA	FRONTAL AREA
	KW	KW	FT^2	FT^2
WIND TURBINES	2 3 4 8	 8	115 180 250 800	 1350
THERMIONIC	*5KW CONTINUOUS		CYLINDER 1 FT DIA 1.5 FT LONG MIRROR 60 FT DIA	
PHOTO VOLTAIC	*5 KW CONTINUOUS		PANEL 70 FT X 70 FT	

*BETHEL, ALASKA IN MAY
60° 47' N

location (60° of latitude is near the practical limit) for solar collecting devices.[35] A major consideration and size limitation in high latitudes is anchoring the converter in the subsoil.[36]

2.1.6.2 Converter System Availability, Reliability and Cost Comparison

In terms of immediate availability 2 to 3 KW wind turbines and photovoltaic panels are off-the-shelf devices with multiple sources. Larger wind turbines (8KW and up) are in high reliability development cycles and some will be available within one year. A solar thermionic device has not been demonstrated. One reference[37] states the technology is available and could be demonstrated with moderate technical risk in two years.

Reliability of smaller wind turbines is higher than larger wind turbines because more smaller wind turbines have been operating over a longer period and thus have a more intensive development base. Solar photovoltaic and solar thermionic devices are potentially reliable because of the absence of moving parts.

Converter system cost in dollars per kw gives the wind turbine an advantage partly because of a more mature technology. The cost of solar photovoltaic converters is currently high but can be expected to become competitive with wind turbines as use of solar panels increases. Solar thermionic can also be expected to decrease in cost per kw after successful demonstration and increased use (see Table 2.14).

2.1.6.3 Converter System Recommendations

For the short term remote site application (available within one year) the 8 KW high reliability wind turbine is an attractive converter choice. Multiple sources are available bringing favorable cost competition. An alternate choice is 2 to 3 KW off the shelf wind turbines. The significant disadvantage of the smaller turbine is the large number of units required for a given output.

TABLE 2.14

CONVERTER SYSTEM AVAILABILITY, RELIABILITY, AND COST COMPARISON

	AVAILABILITY	PREDICTED RELIABILITY	CONVERTER SYSTEM COST
WIND TURBINES	2-3 KW OFF-THE-SHELF	4	12 K/KW
	8 KW 6 MO-1 YR	4	8 K/KW
	20 KW 1 YR	3	10 K/KW
THERMIONIC**	2 YEARS MINIMUM TIME TO DEVELOP SUITABLE SYSTEM	5	15 K/KW*
PHOTO VOLTAIC	OFF THE SHELF	4	60-105 K/KW*

* 1 KW continuous output (6-7 KW peak output).

** Solar thermionic devices have not been demonstrated.

Two choices appear feasible for long term remote site converter selection. Particularly attractive for remote sites with negative correlation of wind and sun[38] is blending high reliability wind turbines with solar photovoltaic panels. In a region of negative correlation required storage decreases since the wind and sun contribute power at different times. An alternate long term choice in place of photovoltaic is development of a 20 KW thermionic system. The potential of combining the thermionic cycle with a fluid cycle suitable for remote site use could increase system efficiency considerably.

2.1.7 Power Conditioning

The use of power conditioning adds a great dea' of flexibility to the system and aids the modularity concept. The conceptual system with the power conditioning in more detail is shown in Figure 2.4. Each module includes its own inverter controlled by a master oscillator to insure that all inverters operate at the same frequency and phase. All of the modules are paralleled on a common bus which feeds a buffer transformer that also serves to filter harmonics. A processing unit is included which serves to control the overall operation of the power system; regulate the energy storage system, control switching among energy storage, input energy converters; and back up diesel power. It also provides a capability for built-in test equipment to check the functioning of the system and each of the major subsystem components. The characteristics of the power conditioning components are given in Table 2.15.

2.2 PHASE I RECOMMENDATIONS AND CONCLUSIONS

It is recommended that the near term optimum power system configuration be composed of a sealed lead acid battery energy storage system in conjunction with modular units of advanced wind turbines. The selection of the sealed lead acid battery system for energy storage is based on the near term availability, relatively low cost, reasonable weight and volume and

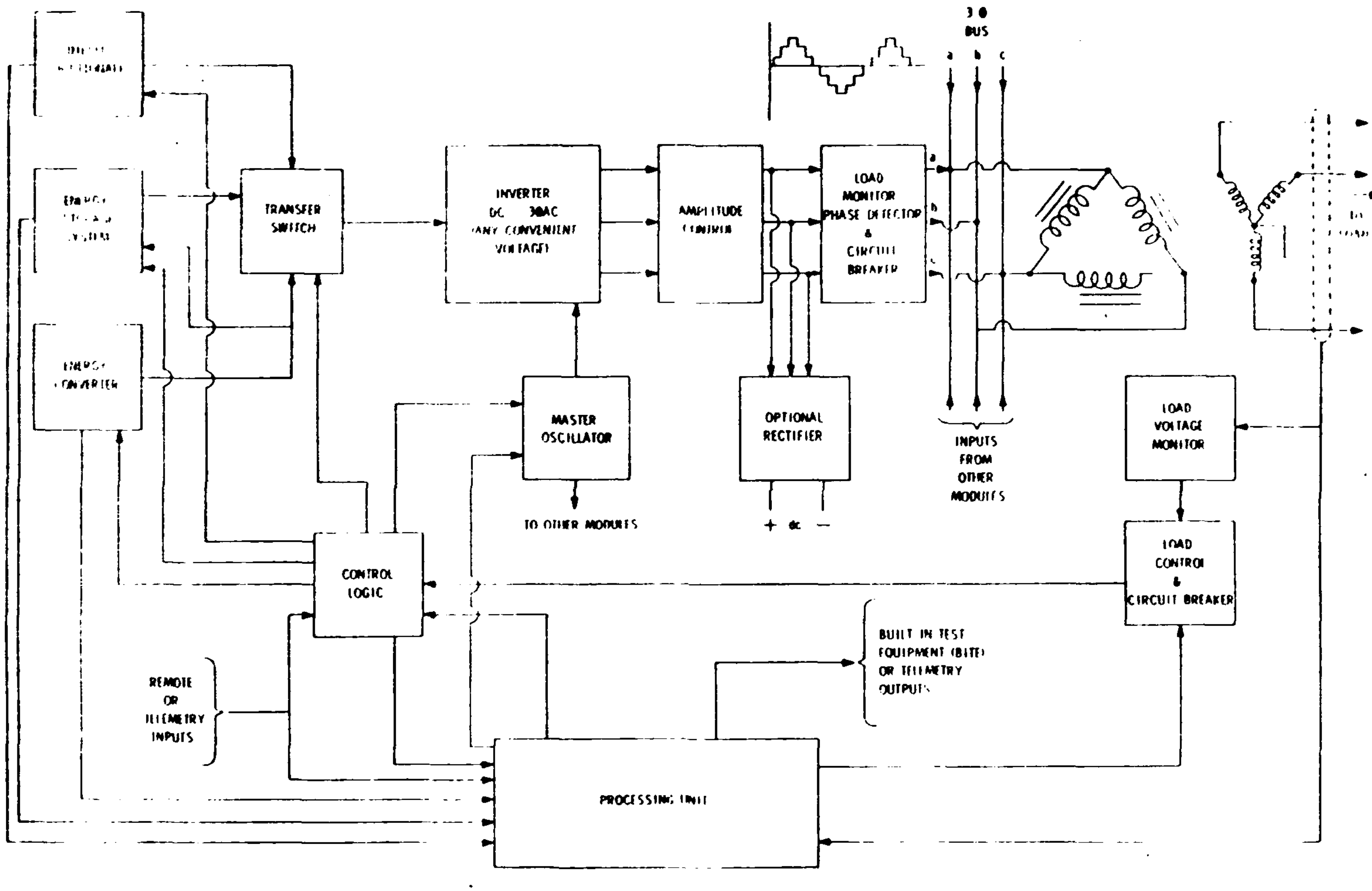


Figure 2.4 Conceptual System Configuration (Power Conditioning Detail)

TABLE 2.15

POWER CONDITIONING COMPONENT CHARACTERISTICS

	Weight	Volume	Cost (K)	Efficiency
Inverter	35#/KW	1 ft^3/KW	1/KW	.8-.9
Buffer Transformer	20#/KW	0.3 ft^3/KW	.25/KW	.98-.99
Transfer Switch	25#	0.5 ft^3	2	N/A
Switching Control Logic	10#	0.1 ft^3	1	N/A
Processor	75#	3 ft^3	5-20	N/A

good efficiency. The energy converter system recommendation is the nominal 8 KW wind turbines now being developed and tested by a number of industries under Department of Energy Sponsorship. These turbines have design goals of high reliability, good efficiency, and low cost. Alternate choice for the wind turbine is the nominal 2-3 KW systems now being manufactured by a number of industries. These units are available off-the-shelf and have good efficiency and low cost. The major drawback of these units is their small KW output.

The system concept described is flexible and versatile permitting use in a wide range of applications many of which have a highly visible need in remote areas. Experience in the operation of alternate energy systems is needed to start compilation of a data base on cost, reliability, maintainability, and performance. This data base would provide engineers the needed information to design optimum alternate energy systems for future use. Demonstration of this type of energy system would have national impact.

It is recommended that the design of the proposed system be started immediately to establish the criteria for the demonstration system. In addition, consideration should be given to developing and demonstrating a hybrid energy converter system, composed of an advanced wind turbine, solar photovoltaic and/or solar thermionic conversion, coupled with an advanced energy storage system.

SECTION 3

DESIGN AND ANALYSIS OF A WIND ENERGY SYSTEM FOR BAR MAIN, BARTER ISLAND, ALASKA

3.1 DESIGN CONSTRAINTS

3.1.1 Design Requirements

The design requirements for the wind energy system for Bar Main, Alaska are two wind turbines in stand alone modules. The system requires sufficient redundancy to insure against single point failure. The system design permits the lead acid storage batteries to be charged by either the wind turbine or, in the event of insufficient wind, the power grid.

3.1.2 Meteorological Conditions at Design Location

Temperatures range from -59°F to +75°F[39,40] at Barter Island, Alaska. The prevailing easterly wind varies from monthly averages near 10 miles per hour in the summer to approximate monthly averages of 15 miles per hour in the winter.[39,40] Mean annual snowfall of 46 inches yields 4.8 inches of water equivalent.[39,40] Relative humidity varies from 67% to 97%.[39,40]

3.2 SYSTEM DESIGN AND ANALYSIS

The proposed system was designed with concern for reliability and durability since production units will be required to operate for long lifetimes, in sometimes hostile environments, with minimum maintenance. Even though the system design specified operation with an existing power grid, it is expected that many of these alternate energy source systems will be used without a supporting grid and have only a few kilowatts of power output capability. It was also envisioned that, since these systems will most probably operate at remote sites, it would be highly desirable for them to have a capability for operation in a degraded mode of power output (i.e., no single point failure would totally disable the power system). Growth potential for the system was also a consideration, so that future additions of solar converters or more wind turbines could be facilitated. The requirements for these alternate energy source power sources are, in many ways, similar to power sources used aboard spacecraft and satellites. Many of the concepts used in the design of this alternate energy source power system are similar to those which have been successfully employed in space power systems.

3.2.1 Common Bus Concept

The specification designation of lead acid batteries permitted the employment of the floating bus concept which has been used in automotive, stationary battery and uninterruptable power system applications. Similar arrangements have been used in space power systems except that a charger is used to control the charging of the commonly used nickel cadmium batteries. The nickel cadmium batteries have a tendency to become thermally unstable during constant potential charging while the lead acid batteries do not.

A simplified diagram of the conceptual system is shown in Figure 3.1. To avoid synchronization problems with alternating current outputs from the wind turbines, the output of each turbine is converted to direct current and then the two machine outputs are connected in parallel. The lead acid battery is then connected in parallel with the generator outputs so that the battery then floats on the generator output and then forms a common DC bus. The input of an inverter is connected in parallel on the bus to convert the DC power to the required AC power. The transformer filters harmonics from the output and serves as a buffer between the inverter and load.

Figure 3.2 shows schematically how energy flows through the system. The output from the wind turbines is fed directly to the load

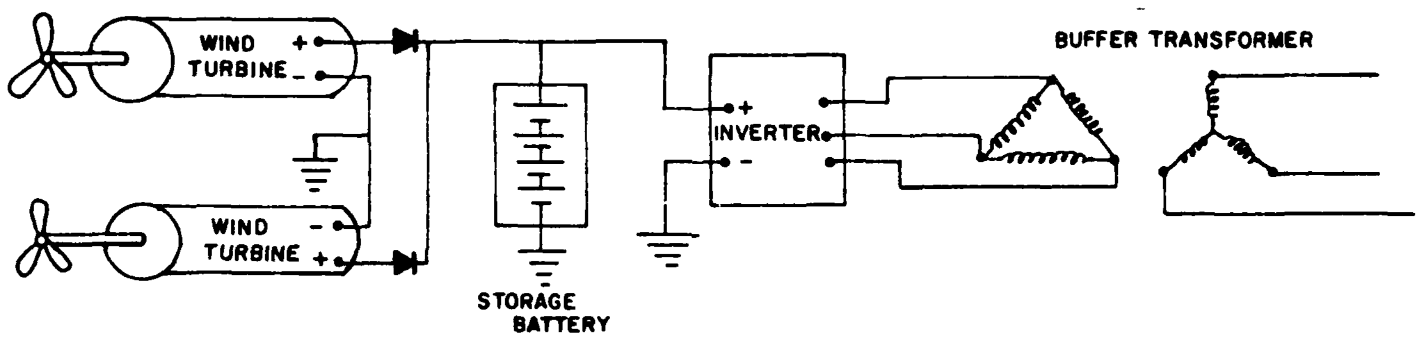


Figure 3.1 Recommended/Proposed Wind Turbine/Energy Storage Power System Configured with AC Output

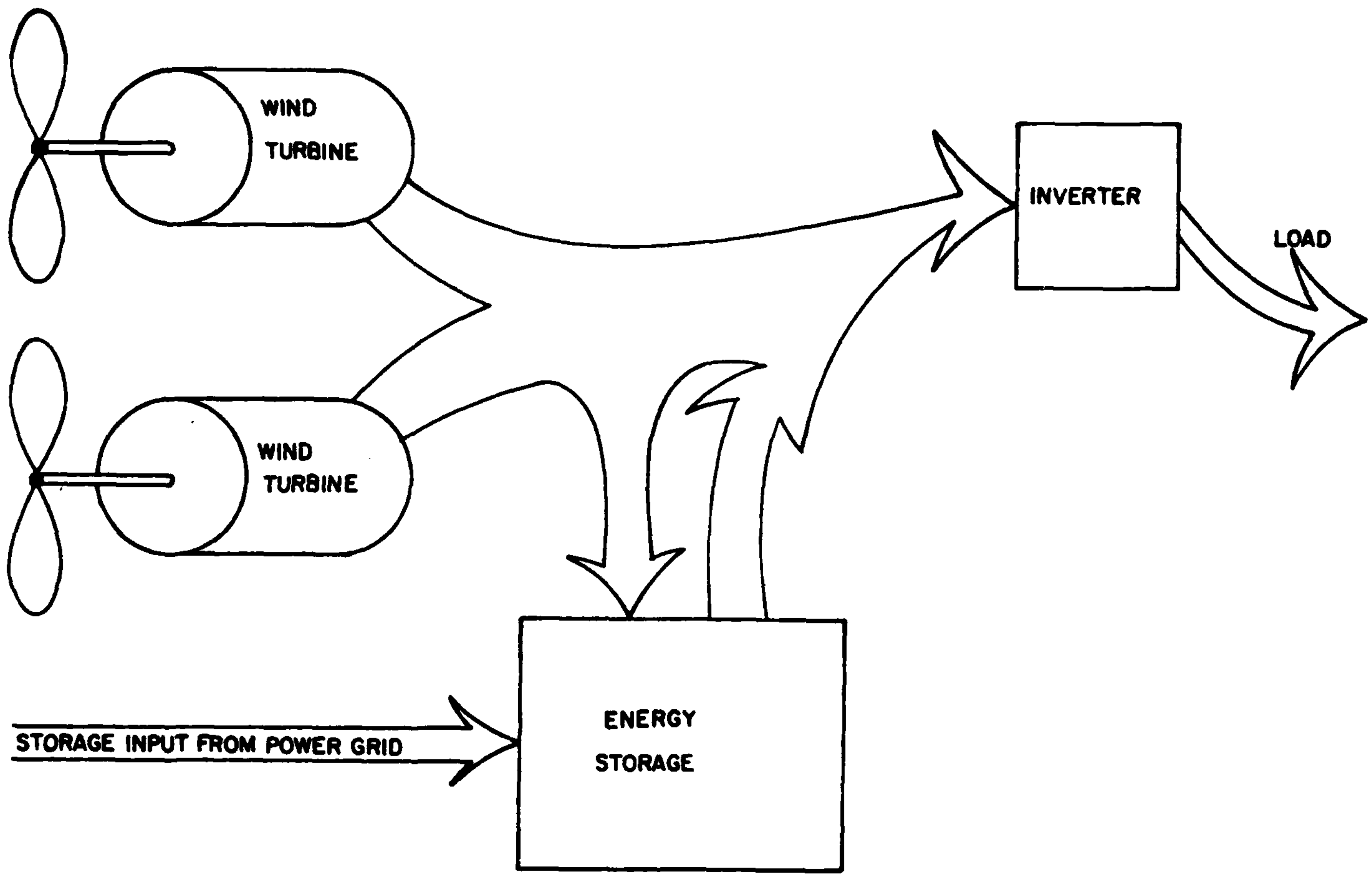


Figure 3.2 Schematic Flow of Energy Through System

and the battery scavenges any power in excess of the load from the bus. In the event that the output of the wind generators is below the required load power, the battery discharges into the bus and provides load power.

A better feeling for the dynamic operation of the system can be developed by examining the behavior of each of the individual components and their characteristics. The inverter reflects the load on to the bus with an appropriate multiplying factor for efficiency. It will take the power needed from the bus as long as the bus voltage remains in the design operating range. The battery is a very low internal impedance device and will draw, during charging, from the bus sufficient current to match its terminal voltage to that of the bus. The battery does have an open circuit or neutral voltage at which it neither charges nor discharges. The open circuit voltage is determined from thermodynamics by the Nernst equation.

$$E^{o} = \frac{-\Delta G^{o}}{nF} = E \text{ open circuit} \qquad (3.1)$$

where

E^{o} = theoretical potential at standard conditions (volts)

ΔG^{o} = standard free energy change for the reaction (kcal/mole)

F = Faraday constant (23.06 kcal/mole volt)

n = number of moles of electrons per mole of product

If the battery voltage rises above this voltage it is charged, and below this voltage, it is discharged. This is shown schematically in Figure 3.3.

The wind turbine consists of a propeller, gear box, governor, and electrical generator. This device produces electrical power output approximately proportional to the cube of the wind speed. In order to make the output of the wind turbine compatible with the batteries and the common bus concept, a voltage regulator is used which limits the maximum voltage output of the generator to a preset value,

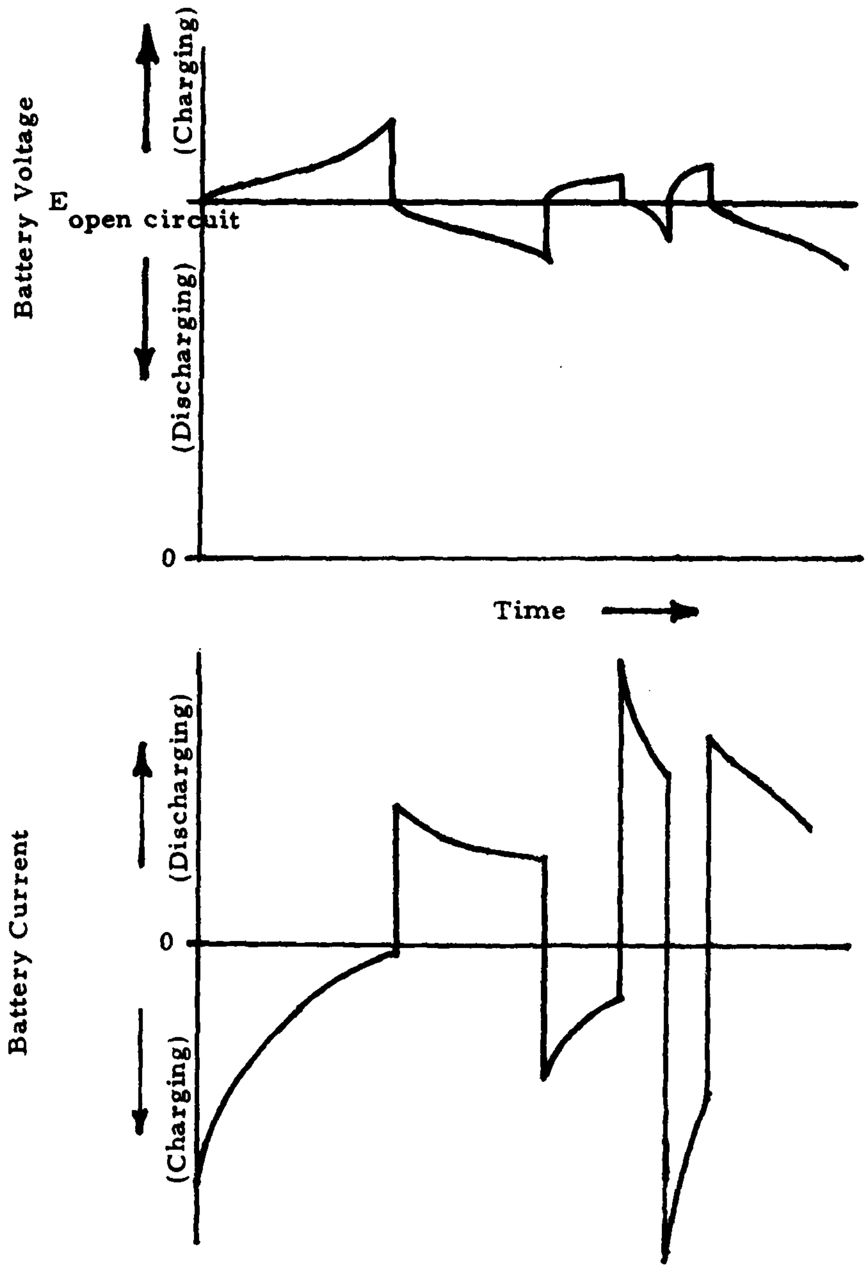


Figure 3.3 Typical Battery Characteristics

which, if desired, could be temperature compensated. The voltage regulator also compares the generator output current with a reference value and reduces the output voltage below the maximum value to control the output current at a level which will not damage the generator. The desired result is an output current voltage relationship as shown in Figure 3.4. This control function is achieved by changing the field current of the electrical machine. The output power of the generator is approximately proportional to the square of the field current. The electrical machine is prevented from drawing power from the bus during low wind conditions by an isolation diode.

Using the preceeding concepts, the operation of the system is as follows. Assume that a relatively steady load is applied to the inverter and the wind is not blowing but the batteries are fully charged. The batteries will supply power to the bus which will flow through the inverter to the load. This action will continue until the batteries are depleted or until the wind speed increases to a point where the wind turbine supports the bus load. Consider the case where the wind turbine can supply only a part of the total load (i.e., wind is blowing but the speed is not sufficient to support the total load), perhaps 50 percent of the load. In this case, the wind turbine will provide 50 percent of the load and the reaminder will be supplied by the batteries. In both of the preceeding cases the bus voltage will be determined by the battery discharge characteristics. The last case to be considered is where the wind speed has increased to a value where the wind turbine is generating power in excess of the load requirements. The battery voltage will rise to a value greater than its open circuit value and begin to charge. The battery voltage will rise during charging and will control the bus voltage level until it reaches near full charge, at which time the maximum voltage limit will be reached and the voltage regulator will reduce the field current to maintain a constant output voltage from the wind turbine.

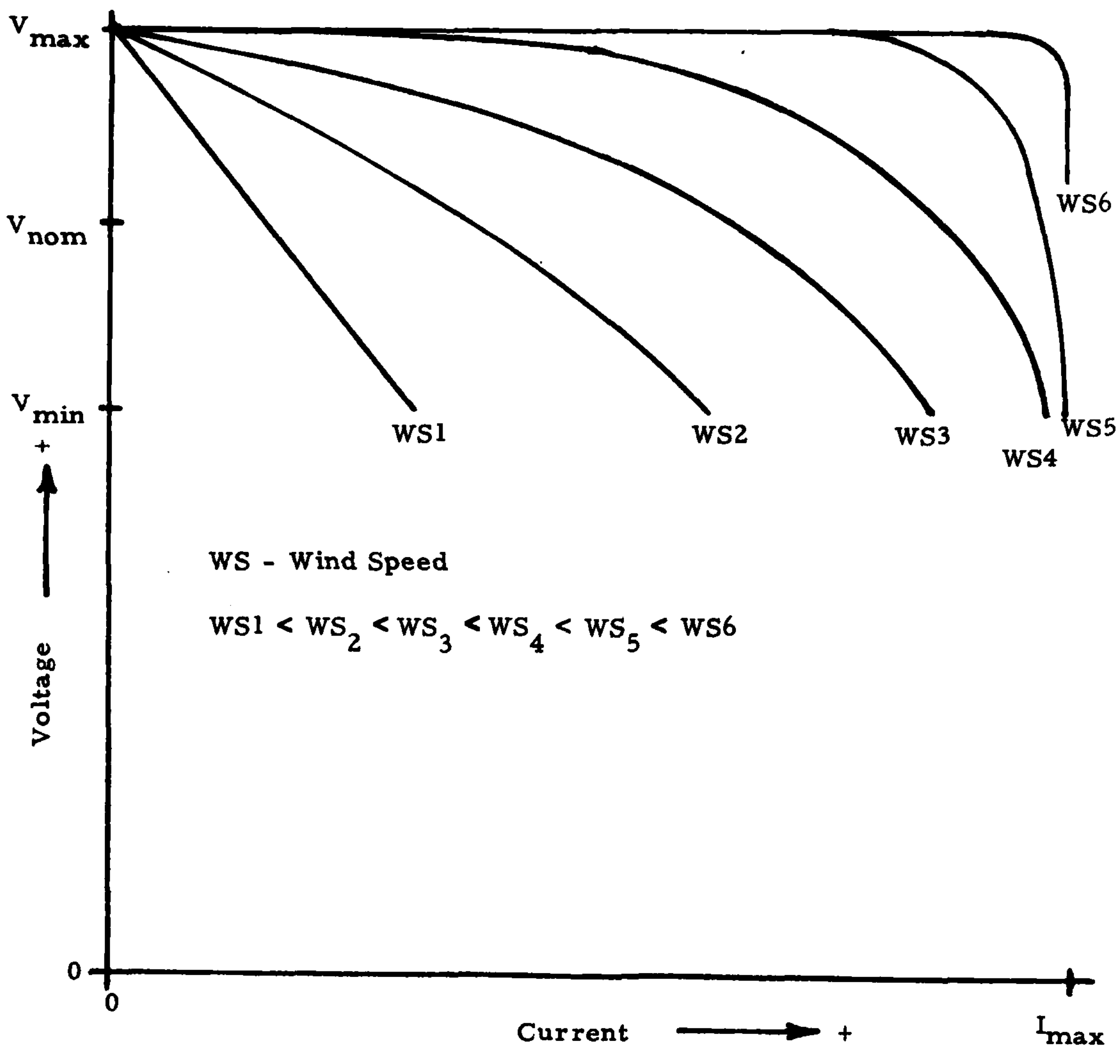


Figure 3.4 Desired Wind Turbine Generator Output Characteristics

3.2.1.1 Development of Output Equation

Using the conceptual configuration of Figure 3.2 an approximate steady state output equation was developed. The input to the storage system from the power grid was ignored in the development of the output equation; therefore, the equation is representative of a system which can stand alone without a supporting or backup power grid. Figure 3.5 shows the system model used for derivation and terminology purposes. The terms are defined to be:

P_{WT} = power output from one wind turbine

P_{SI} = power input to the energy storage system

P_{SO} = power output from the energy storage system

P_{IV} = power input to the inverter

P_L = power output from the inverter to the load

η_S = efficiency of storing energy

η_{IV} = inverter efficiency.

The power produced by the wind turbines is split into two components, that which goes directly to the inverter and that which goes into energy storage. Since there are two wind turbines, the power generated is $2P_{WT}$. Thus,

$$2P_{WT} = P_{IV} + P_{SI} \tag{3.2}$$

The power output from the wind turbine must be known from experimental data or manufacturers' design calculations. Using a least squares polynomial fit routine contained in the University of Dayton's computer program, a fourth order polynomial was found to fit the data supplied by one of the manufacturers for power output as a function of wind speed. The calculated values were within one percent of the supplied values over the wind speed range of interest. The fitted

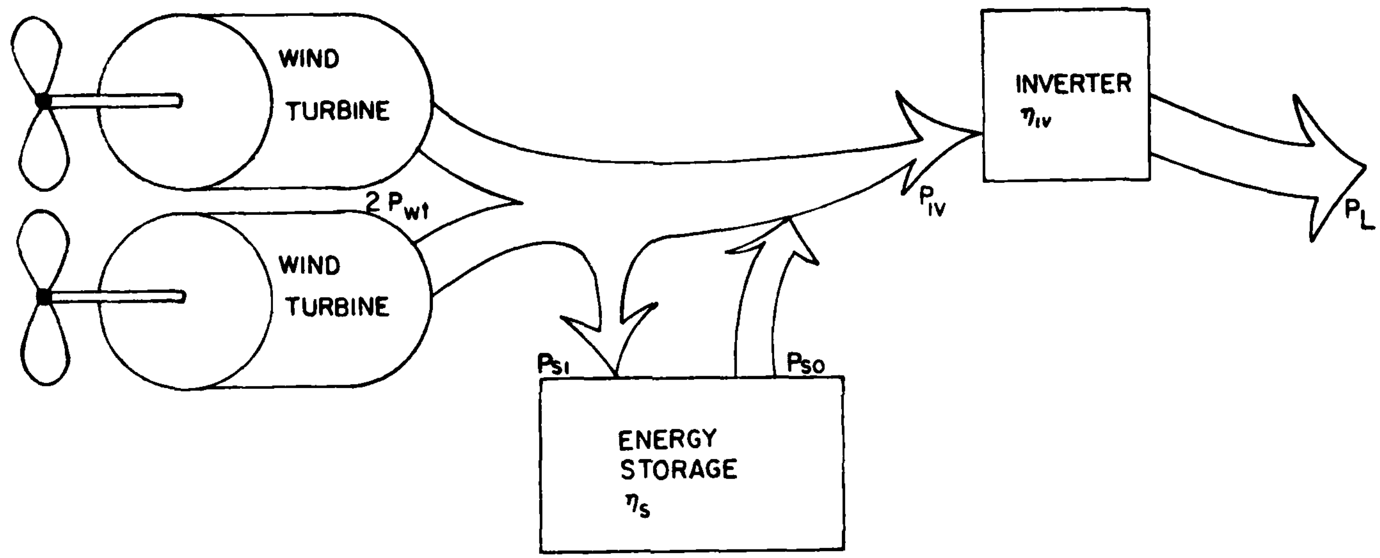


Figure 3.5 System Model Used for Derivation and Terminology Purposes

polynomial was also checked using another computer library program to insure that it or the first derivative did not have any roots in the wind speed range of interest. These checks insured a monotonic increase of the polynomial. The fitted polynomial is given below for illustration purposes but it must be noted that it is only useful for one of the wind turbines examined and then only over a range of wind speeds from 5 to 20 miles per hour. The fitted polynomial is:

$$P_{WT} = 8.24 \times 10^{-5} S_W^4 - 5.76 \times 10^{-3} S_W^3 + .103 S_W^2 - .449 S_W - 7.8 \times 10^{-4} \quad (3.3)$$

where

S_W = wind speed (mph)

P_{WT} = wind turbine electrical power output (kw)

The load power is simply the product of the inverter input power and the inverter efficiency.

$$P_L = P_{IV} \cdot \eta_{IV} \quad (3.4)$$

The power levels associated with the energy storage unit are slightly more complicated in that an energy balance must be made on the energy storage system. The power output from the energy storage system times the period which the battery discharges is the energy supplied. More accurately this should be written as an integral, but for the purposes of this analysis the power output was assumed constant. This assumption places a further limitation in that sharing of the load between the battery and wind turbine is not permitted. Continuing with the energy balance, the energy input to the storage system is the power input to the storage system multiplied by the time to change the storage system. Again, this should more accurately be described as an integral but constant or steady state input power was assumed in this simplified analysis. The simplified energy balance thus becomes:

Stored Energy Output = Storage Efficiency · Energy Storage Input

or:

$$P_{SO} \cdot t_D = \eta_S \cdot P_{SI} \cdot t_c \qquad (3.5)$$

where

t_D = discharge time

t_c = charge time

From Figure 3.5, it is apparent that during battery discharge the inverter input power is equal to the storage system output power. This excludes sharing of the load between the storage system and the wind turbines. Noting this and substitution of Equation 3.4 yields:

$$P_{SO} = P_{IV} = \frac{P_L}{\eta_{IV}} \qquad (3.6)$$

Rearranging Equation 3.5 results in:

$$P_{SI} = \frac{P_{SO}\ t_D}{\eta_S\ \ t_c} \qquad (3.7)$$

Substituting Equation 3.6 into Equation 3.5 yields:

$$P_{SI} = \frac{P_L t_D}{\eta_{IV}\eta_S t_c} \qquad (3.8)$$

Substituting Equations 3.6 and 3.8 into Equation 3.2 yields:

$$2P_{WT} = P_{IV} + P_{SI} = \frac{P_L}{\eta_{IV}} + \frac{P_L}{\eta_{IV}}\ \frac{t_D}{\eta_S t_c} = \frac{P_L}{\eta_{IV}}\left(1 + \frac{t_D}{\eta_S t_c}\right) \qquad (3.9)$$

Solving Equation 3.9 for the load power yields:

$$P_L = 2 \cdot \eta_{IV} \cdot P_{WT}\left(\frac{1}{1 + \frac{t_D}{\eta_S t_c}}\right) = \left(\frac{2\eta_{IV}\eta_S t_c}{\eta_S t_c + t_D}\right) P_{WT} \qquad (3.10)$$

Finally substituting the fitted polynomial, Equation 3.2, into Equation 3.10 gives a relation to determine load power for a given battery efficiency, inverter efficiency, charge time, discharge time, and wind speed.

$$P_L = \left(\frac{2\eta_{IV}\eta_S t_c}{\eta_S t_c + t_D}\right)\left(8.24 \times 10^{-4} S_w^{\,4} - 5.76 \times 10^{-3} S_w^{\,3} + .103 S_w^{\,2} - .449 S_w - 7.8 \times 10^{-4}\right) \qquad (3.11)$$

Caution must be used in the application of Equation 3.11 due to limitations previously noted on the polynomial term.

3.2.1.2 Analysis of System Performance

Equation 3.11 was used to analyze system performance except that values were input for the wind turbine power output instead of using the wind speed polynomial. The following ranges of variables were investigated.

Wind Speed:	10, 12.5, and 15 miles per hour
Discharge Time:	6, 12, 18, and 24 hours
Inverter Efficiency:	60-95 percent in 5 percent steps
Battery Efficiency:	70-90 percent in 5 percent steps
Charge Time:	1-100 hours in 3 hour steps

A computer program was written to mechanize this analysis. The computer program is listed in Appendix B which incorporates a curve plotting routine. The output was a series of approximately 500 curves of steady state system power output as a function of charge time. Four of these curves are shown in Figure 3.6 for efficiencies representative of the equipment to be used and the annual average wind speed of Bar Main. A cross plot of the Figure 3.6 data and other similar curves at higher and lower wind speeds is shown in Figure 3.7. It is apparent from this figure that a 10 kilowatt system with a reasonable amount of energy storage is not possible with the two proposed nominal 8 kilowatt DOE wind turbines at the Bar Main location.

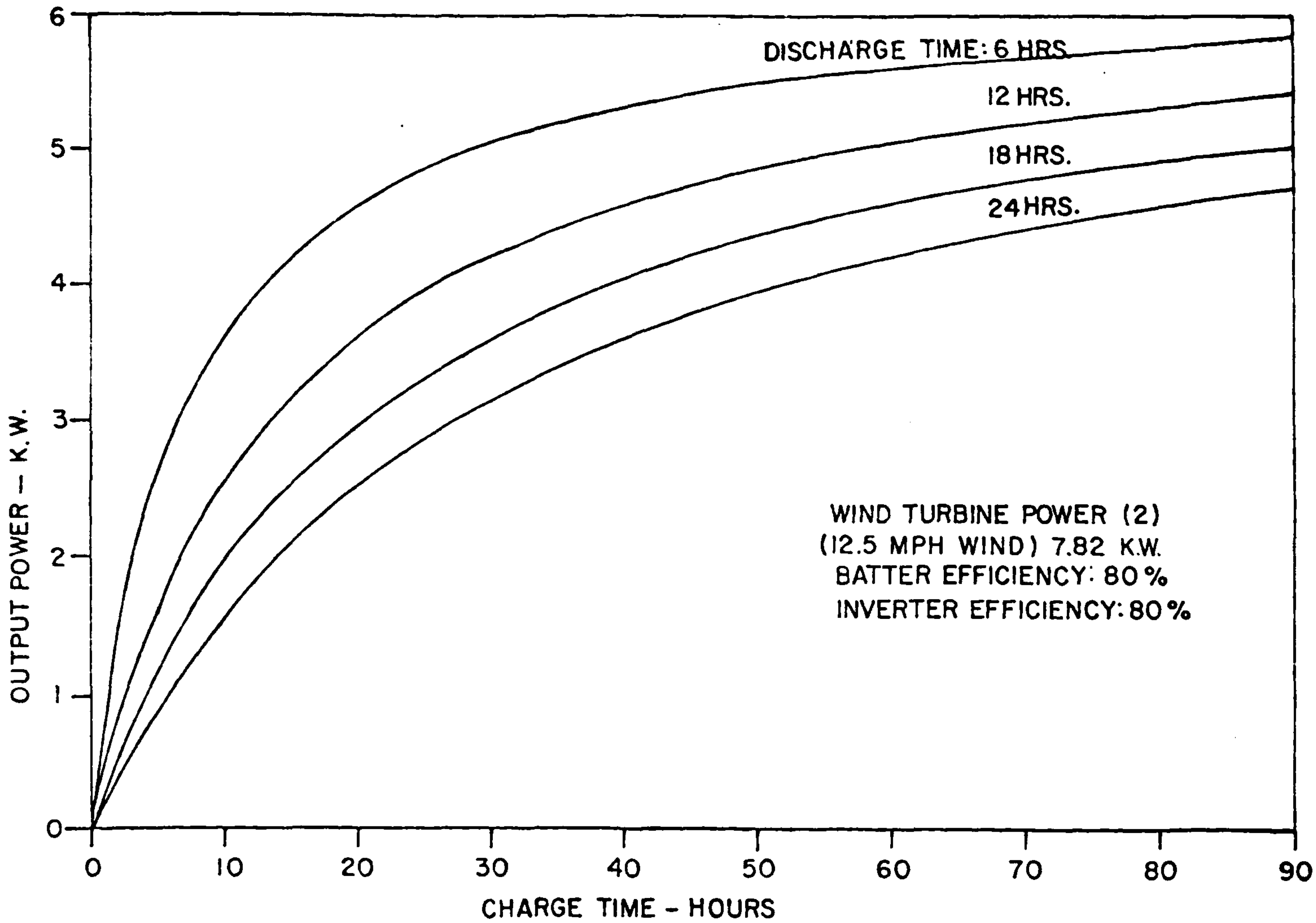


Figure 3.6 Load Power as a Function of Charge Time

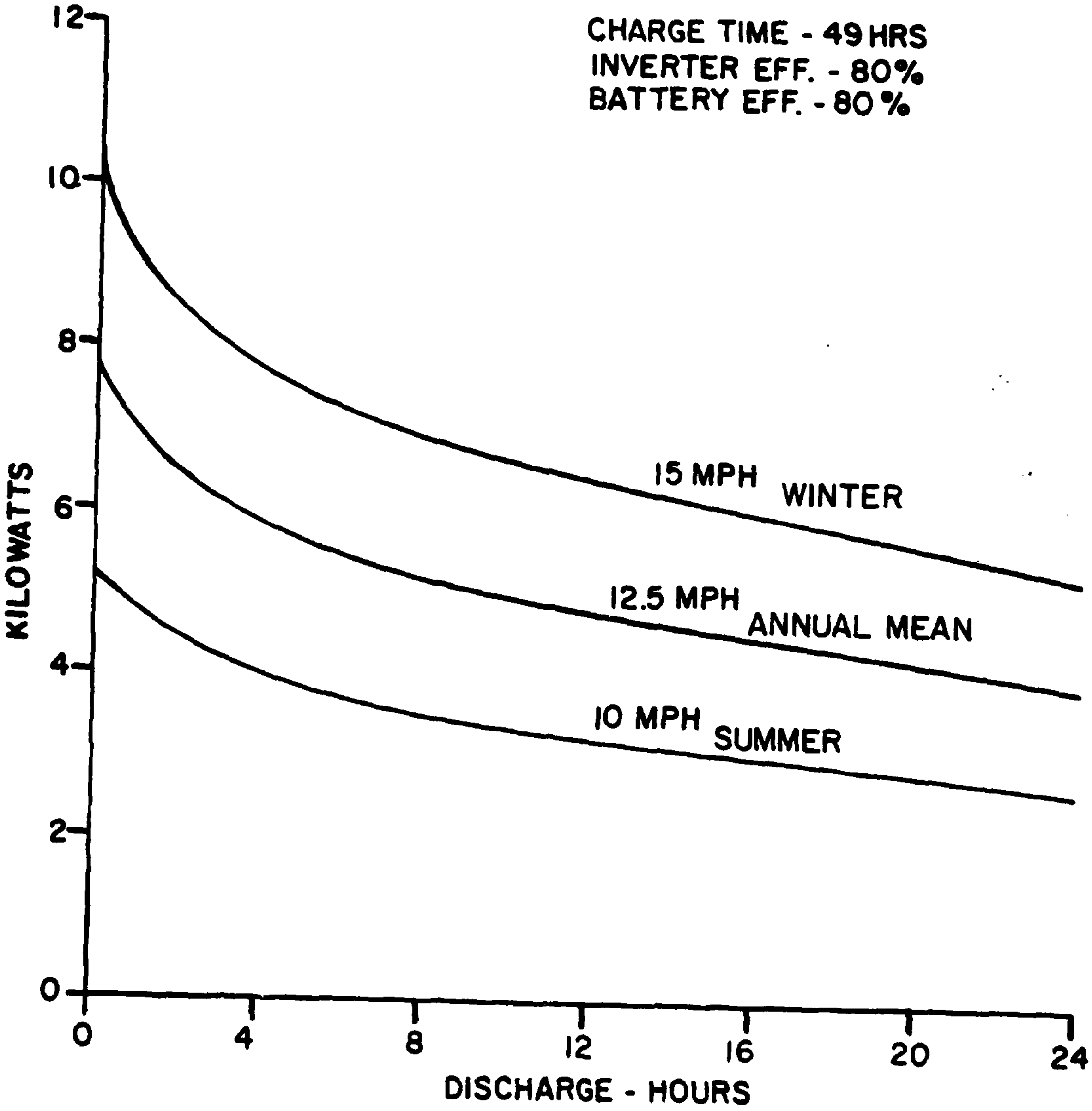


Figure 3.7 System Power Output

3.2.2 Component Analysis

During the development of the system concept, the major system components and/or subsystems; battery, inverter, wind turbine, and tower, were analyzed in detail. The results of these analyses are discussed below.

3.2.2.1 Battery

Lead acid batteries were specified for consideration during this phase. There are four basic types of lead acid batteries that can be used. These four types are: sealed, automotive, industrial, and standby. A clear distinction is needed relative to the sealed type lead acid batteries. These are truly sealed batteries so that virtually all of the gases generated during charging and overcharging are recombined within the battery cells. Water additions to these batteries are never made and virtually no gases or liquids are emitted from the batteries during normal operation. This distinction is made because some of the more modern automotive lead acid batteries do not require water additions and are said to be maintenance free or in some cases "sealed". These types of automotive batteries, while emitting less gases than the conventional automotive batteries, do emit some gases during overcharging and require venting. Both the industrial and standby battery types require venting of gases generated during charging and overcharging. Battery venting is an important consideration for two reasons. First, since gases are being emitted, replacement water must be added. This is important from a maintenance standpoint because water must be transported to the remote sites and time is consumed in checking and adjusting, if necessary, the water level. This also represents an area for human error and possible battery failure. The cells could be overfilled and eject excess electrolyte which could short circuit the battery or cause corrosion problems. Another possible error is the drying of a cell and resultant open circuit due to a human error of adding too little water to one of the cells. The second reason for venting considerations is the heating of replacement air that must be circulated to prevent the accumulation of explosive hydrogen gas. As estimate of this heating requirement is made below.

The battery is assumed to operate at 68°F. This is a temperature compatible with ambient environments in heated/cooled shelters and is also a temperature near the optimum for battery performance and life. The lowest mean monthly temperature for Bar Main is -26°F.[40] It is conservatively assumed that there is no heat transfer from the battery to the replacement air. The battery size is 400 kilowatt hours. This number is justified later in this section. The battery overcharge voltage is 115 volts (2.45 volts per cell) which is also justified later in this section. The battery current in amperes at this voltage is approximately 0.015 times the rated capacity in ampere hours.[11] The nominal battery voltage is 100 volts (2.12 volts per cell); therefore 47 cells are used in series. The overcharge current is:

$$400{,}000 \text{ watt hours} \times 0.015 \, \frac{\text{amperes}}{\text{ampere hour}} \times \frac{1}{100 \text{ volts}} = 60 \text{ amperes}$$

Since the 60 amperes flows through each of the 47 series connected cells, the total number of ampere hours of Hydrogen generated in 1 hour is:

$$60 \text{ amperes} \times 1 \text{ hour} \times 47 \text{ cells} = 2820 \text{ ampere hours}$$

From Faraday's law we know that 2.016 grams (1 gram molecular weight) of Hydrogen is equivalent to 2 times 96,500 coulombs of electricity or 53.61 ampere hours. Therefore $\frac{2820}{53.61} = 52.6$ gram molecular weight equivalents of Hydrogen per hour. At Standard temperature and pressure the volume of one gram molecular weight of gas is 22.4 liters. The volume of Hydrogen generated is

$$52.6 \text{ gram molecular weights} \times 22.4 \, \frac{\text{liters}}{\text{gm molecular weight}}$$

$$\times\ .03531 \, \frac{\text{ft}^3}{\text{liter}} = 42.37 \text{ ft}^3 \text{ of Hydrogen generated per hour.}$$

Hydrogen is combustible in air over the range 4 percent to 75 percent by volume.[41] It is not practical to maintain a hydrogen concentration of greater than 75 percent; therefore, a concentration of less than 4 percent must be used. Thus, $.04 \times Y = 42.37 \text{ ft}^3$, where Y is the total number of cubic feet of nonflamable mixture. The volume of replacement air required per hour is:

$$.96 \left(\frac{42.37}{.04} \right) = 1017 \text{ ft}^3$$

Using the specific heat of air at constant pressure[41]

$$C_p = .24 \quad \text{BTU/lbm}^\circ\text{F}$$

The density of the air[41] changes from something greater than 0.081 to about 0.074 lbm/ft^3 over the temperature range of interest. For this calculation a value of 0.076 lbm/ft^3 @ 60 F was used.

$$C = C_p \cdot \gamma = .24 \times .076 = 0.018 \text{ BTU/ft}^3 \, ^\circ\text{F}$$

$$\Delta T = 68 - (-26) = 94^\circ\text{F}$$

The rate that heat must be supplied to the replacement air for keeping the hydrogen generated below flammable limits is:

$$q = \text{volume of air} \cdot C \cdot \Delta T = 1017 \times .\text{-}18 \times 94 = 1720.3 \text{ BTU/hr}$$

$$q = 1720.3 \times .2931 = 504.2 \text{ watts}$$

This rate of heat is that required to raise the air temperature from -26°F to +68°F, the minimum amount of replacement air necessary to keep the hydrogen evolved during overcharging from becoming a flammable mixture. In practive the amount of replacement air needs to be greater by a factor of 2.7[42] to 4[43] and thus the heating power requirements would be greater by similar factors. A manifold of the battery cell vents should be considered as a technique for limiting the volume in which the hydrogen is diluted and minimize the heating requirements for the replacement air. A ventilation manifold for use in battery shops is discussed in Reference 44. Another technique for reduction of ventilation air is the use of a relatively low replacement air flow and a hydrogen detector[42] which automatically switches to a high flow of replacement air upon detection of hydrogen approaching combustible limits. Some other references[45,46] discuss ventilation of battery enclosures. One reference[47] states that air changes of 12 times per hour have been routinely used in enclosures that have potential for collection of explosive, toxic, or corrosive vapors. This criteria requires a large amount of heat for replacement air and should only be used after careful consideration of its impact relative to total energy available from the power system. The important fact from the above discussion is that venting requirements must receive careful consideration in cold climates and the heating requirements for the replacement air cannot always be considered negligible.

Based on the increased maintenance requirements and the heating power requirements for vented batteries, the use of sealed batteries seems justified. The technology for these sealed batteries is mature; however, they do not exist in the large sizes needed for a large system such as considered here. Development of larger size units would have considerable payoff for this and related applications.

Sizing of the battery is another critical issue. Phase I effort examined the battery size requirement and that analysis was further refined. The requirement was given during Phase I to deliver 20 kilowatts to the load for a period of 12 hours and this requirement was not changed under Phase II. The load energy requirement is 240 kilowatt hours. This energy is passed from the batteries to the load through the inverter which has an efficiency of about 80 percent. This then dictates a stored energy requirement of 240 ÷ .8 or 300 kilowatt hours. The minimum battery storage size is then 300 kilowatt hours, however, if the batteries are to have good life, they should not be operated such that they do not reach full discharge but rather operated over a range of partial discharge. Figure 3.8 gives charge-discharge cycle life as a function of depth of discharge. An estimate of battery cycle life was made as follows.

Time of one cycle = charge time + discharge time = 72 hours (3 days)

where

> discharge time at nominal power (10 KW) = 24 hours and
> charge time (taken from Section 3.2.1.2 results as a compromise between minimum charge period and system power output, arbitrary choice) = 48 hours

The batteries have an estimated calendar life of 5 years[11] in normal use, however, since service in this application is relatively severe a life of 3 years was used. This is consistent with lifetimes of other components. The cycle life requirement (extreme case) is 3 years x 365 $\frac{\text{days}}{\text{yr}}$ x $\frac{1}{3}$ $\frac{\text{cycle}}{\text{day}}$ = 365 cycles. From Figure 3.8 for 365 cycles, a depth of discharge equal to approximately 75 percent should be used. This requires that the battery be 4/3 the minimum energy storage requirement. The battery size then becomes 4/3 x 300 = 400 kilowatt hours.

A battery storage system of this size should be composed of multiple parallel strings for reasons of reliability, maintainability, handling, and safety. The total ampere hour capacity of the battery is 400,000 (the total energy stored) ÷ 100 (the system voltage) = 4,000. If a single battery string were used, the individual cells would contain 4,000 x 2.12 or 8480 watt hours of energy. Lead acid batteries typically deliver 10-12 watt hours per pound and 1 watt hour per cubic inch. A single cell would weigh between 706 and 848 pounds and occupy a volume of 4.91 cubic feet. A unit of the battery of this size would be extremely difficult to hardle during maintenance and/or overhaul. If an

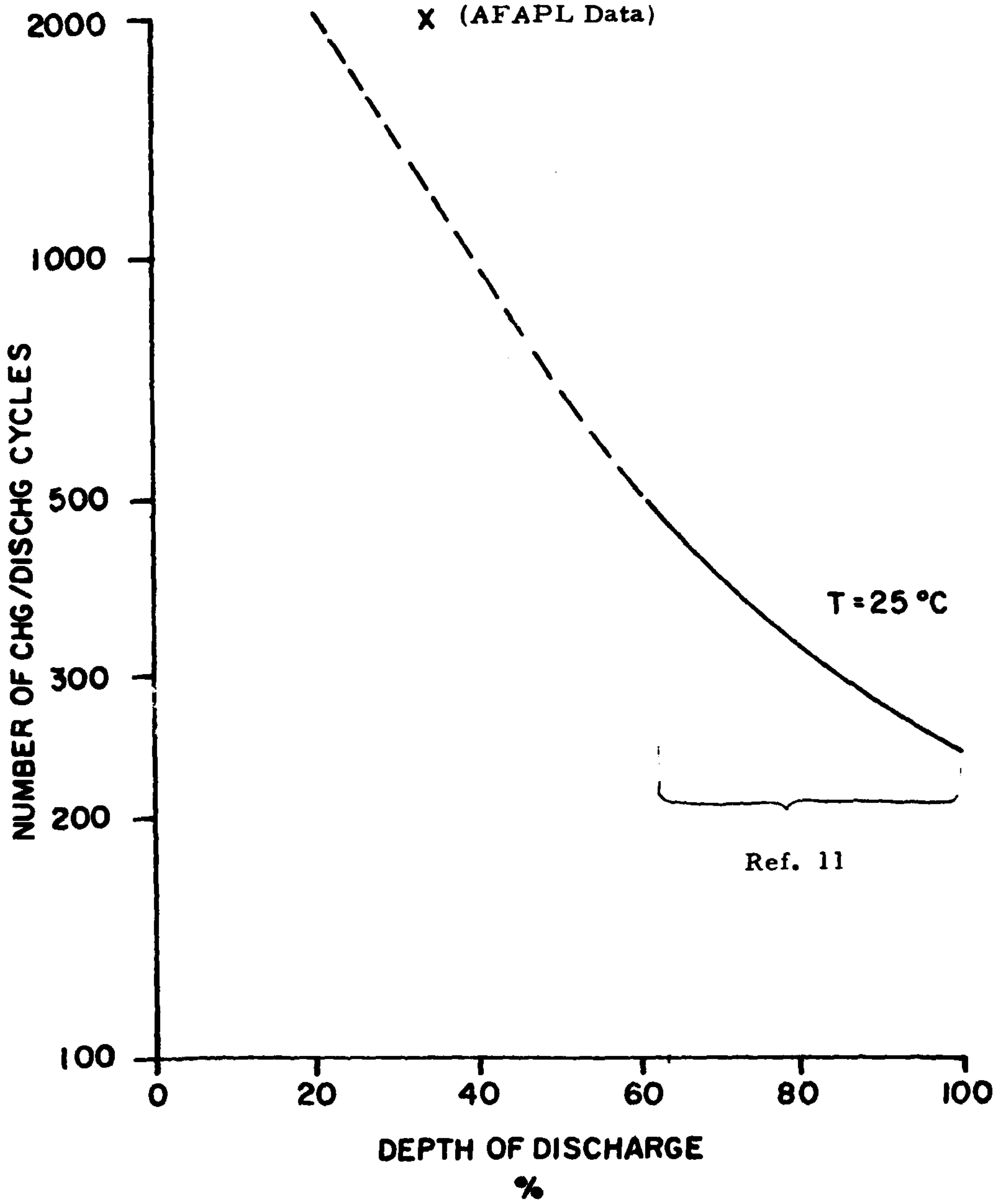


Figure 3.8 Battery Cycle Life

internal short circuit should occur in a single cell of this size a large amount of energy, up to 30.5 megajoules, could be liberated. Furthermore, the failure of any one of the series connected cells would result in a failure of the entire battery system due to a single point failure. Based on results from similar batteries, reliability of a single string would be 0.95.

The above analysis supports parallel strings of smaller ampere hour capacity cells, the number of strings was selected to be a minimum of four. The first approach was to use three parallel strings of which two could support the required load, a concept that has frequently been used in space power systems. Such an approach would slightly oversize the battery system at 450 kilowatt hours. Four parallel batteries of which three can carry the design load meets the size and depth of discharge criteria. Four parallel strings of 1000 ampere hours each would permit failure of one string and still be capable of delivering 300 kilowatt hours of energy. During normal operation only 300 of the battery's 400 kilowatt hours or 75% of its energy would be discharged. Furthermore, the 1000 ampere hour cells would weigh 175-225 pounds and occupy a volume of about 1.25 cubic feet. Cells of this size would be reasonable for handling by two persons without special handling equipment. Cells of this size would still contain a large amount of energy, approximately 7.6 megajoules, to be liberated in the event of an internal short circuit and self destruction. The equivalent parallel reliability for four parallel strings is 0.9999.

A battery composed of four parallel strings would contain a total of 188 cells. This is a large but not unreasonable number of cells to periodically check and maintain. In the event of a cell failure, the faulty cell must be located and its string isolated. A device developed by TMI, Inc.,[48] St. Louis, Missouri for use with aircraft batteries can be adapted for use with batteries of this type. This electronic device samples the individual cell voltages and temperatures. The voltage and temperature of each cell is compared with that of adjacent cells and a reference value. If the difference is greater than some preset threshold value, a signal is generated which can be used to isolate the string containing the faulty cell or warn of impending failure. The device also commits to memory the faulty cell for identification at a later time. The device can also be used during maintenance to identify cells that are operating in a degraded mode but not yet degraded sufficiently to exceed the criteria for failure.

The battery voltage and tolerance were selected in the following manner. A nominal bus voltage was selected which seemed reasonable relative to the amount of power to be handled and the number of series connected battery cells necessary to achieve that voltage. The nominal voltage of 100 volts was selected since: (1) it is reasonably safe without using high voltage safety precautions; (2) it is compatible with state of the art components; (3) current levels are maintained in the range of 100-200 amps and thus wire sizes are reasonable; and (4) it is consistent with a reasonable number of series connected battery cells, 47 if an open circuit voltage of 2.12 volts per cell[11] is used. An upper voltage limit during recharge and overcharge of 2.45 volts per cell or 115 volts for the battery was selected based on the results of tests that have continued over 2 years at the Air Force Aero Propulsion Laboratory, Wright-Patterson Air Force Base, Ohio and data from Reference 11. This voltage results in an overcharge current of about 60 amperes, a recharge time of 14 hours to 100 percent of nominal capacity, and is near the optimum value for maximum cycle life. A higher end of charge voltage could be used with life reductions and higher overcharge currents (i.e. more gas production and water use); however, the charge rate would be higher. The higher charge rate appears to be desirable on an initial inspection however. Figure 3.9 shows that at a windspeed of 25 miles per hour the highest expected power output is about 21 kilowatts. For a storage system sized at 400 kilowatt hours, if all of the 21 kilowatts went into charging the battery, 19 hours would be required or 36 percent longer than the 14 hour design point

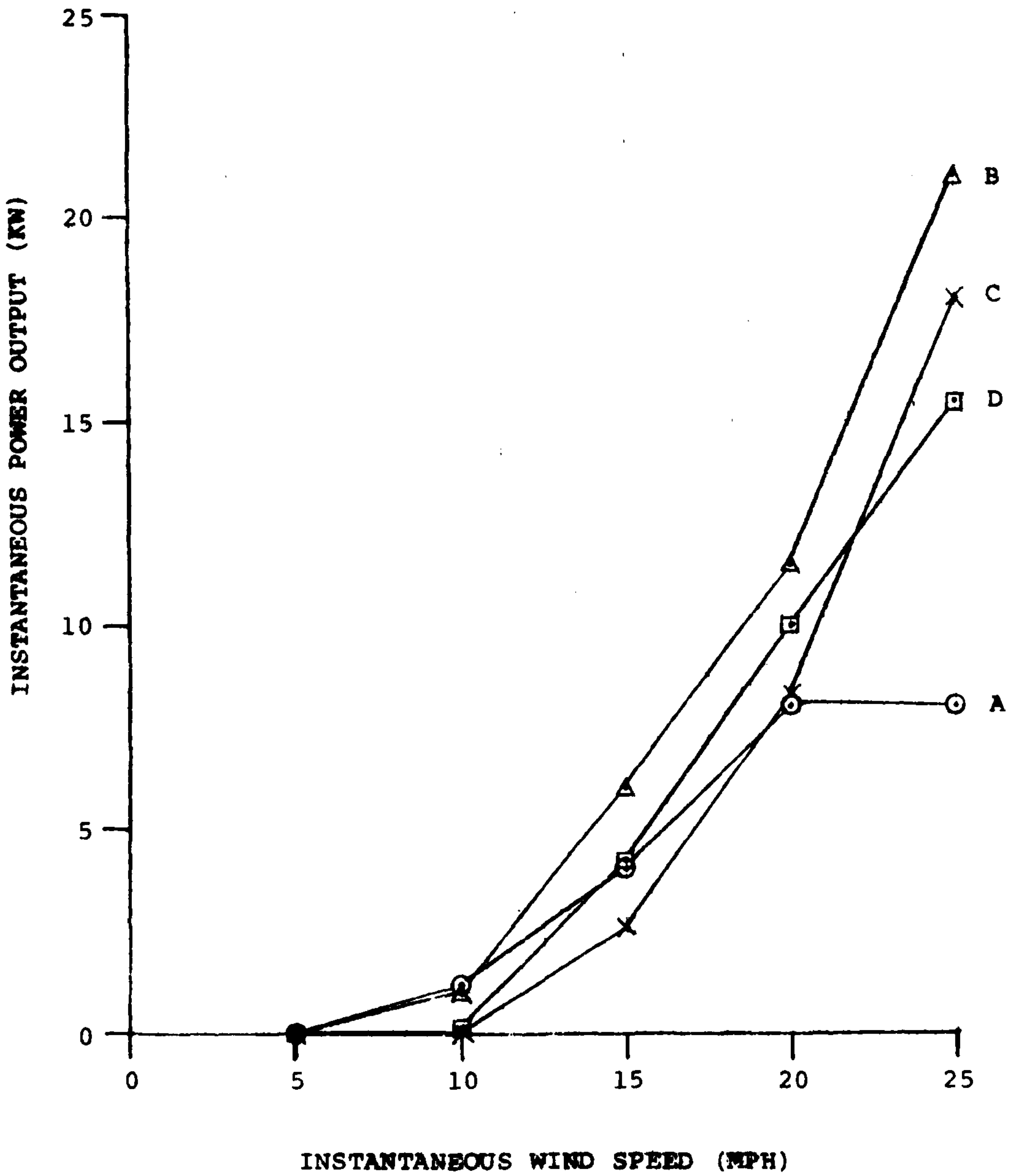


Figure 3.9 Wind Converter Power Output (8 KW Rated Machines)

for a charge at a constant potential of 115 volts. This analysis shows that an end of charge voltage of 2.45 volts per cell or 115 volts for the battery permits the battery to store energy as fast or faster than the wind turbines can convert it the majority of the time. From integrating the area under the uppermost curve in Figure 3.10, the wind blows 25 mph or less 76.5 percent of the time. A minimum voltage of 1.8 volts per cell was selected since very little energy is available below it.[11] This cutoff voltage corresponds to a battery voltage of 85 volts. The range of voltage for the system operation is then 100 ±15 volts.

3.2.2.2 Inverter

The Inverter is a critical block in the power system in that all of the power to the load flows through it. The efficiency of the inverter is the most critical parameter. The input/output equation developed in Section 3.2.1.1, Equation 3.11, shows that the output power is directly proportional to the inverter efficiency. The other parameter is the range of input voltage that the inverter must accommodate. A range of 100 ±15 volts is required. If a single inverter is used, a single point failure is possible. This dictates the use of multiple inverters operating in parallel. A typical single inverter reliability is 0.98. For three inverters operating in parallel, the reliability is 0.9999. Parallel operation of inverters presents some problems of frequency and phase synchronization which must be overcome by the use of control circuits. The Bar Main installation requires operation into an existing power grid so the inverter output must be synchronized in frequency and phase with the power grid. Grid synchronization is not a problem with a "stand alone" system powering a load. The impedance of the load is a parameter that must be considered because low power factor loads can overload the inverter. The inverter response to and recovery from transient load changes is also a parameter of concern because of possible damage to the load.

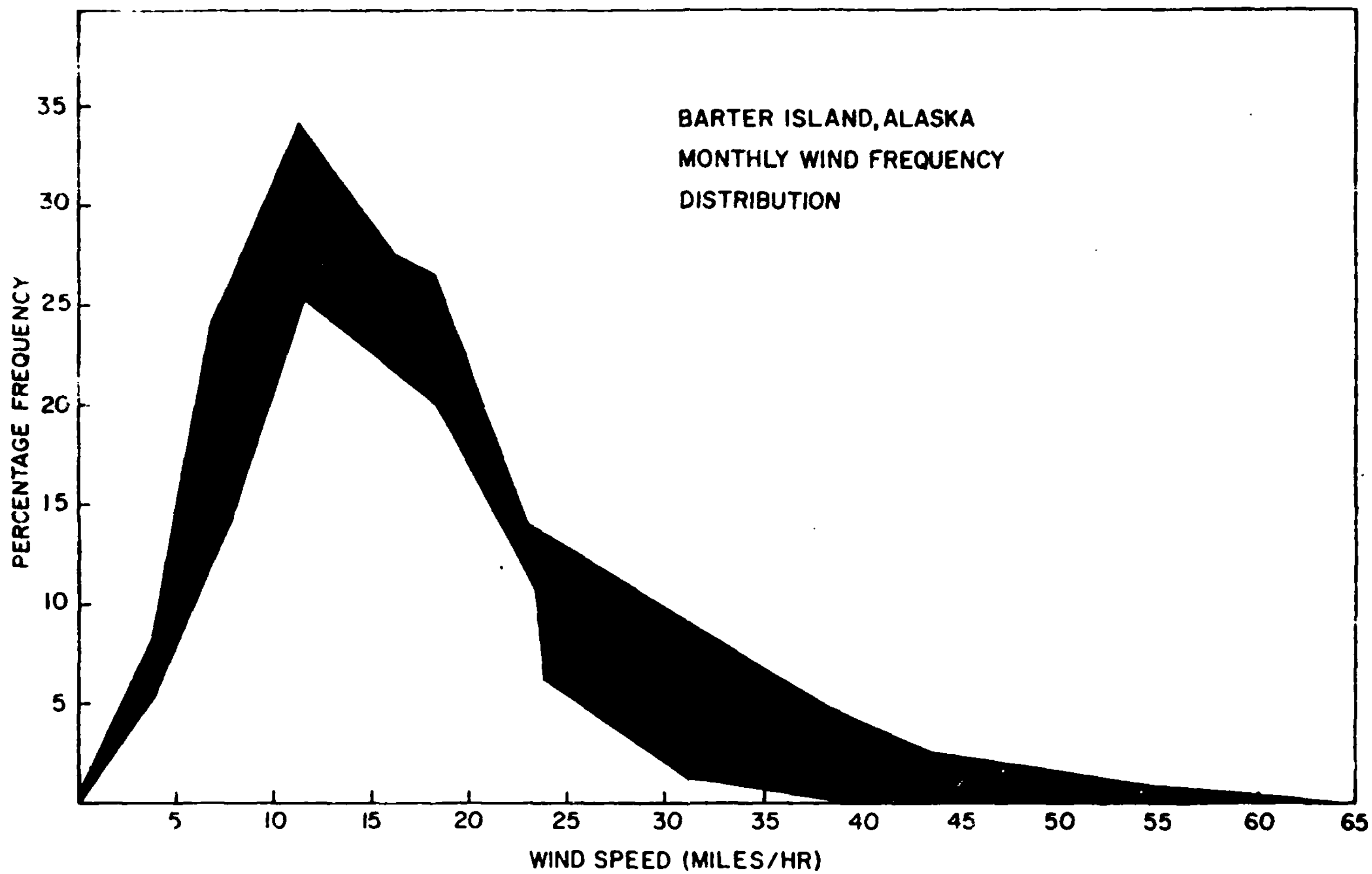


Figure 3.10 Monthly Wind Frequency Distribution at Barter Island, Alaska

Three inverters operating in parallel were selected and sized so that two units could carry the entire load and eliminate the possibility of a single point failure. Therefore each of the three inverters normally operate at 2/3 full load. Two inverters operating at half load could have been selected, however, Figure 3. 11 shows the problem with using two inverters. Ignoring the synchronous inverter curve, operation at 50 percent load is very close to the knee of the efficiency curve. Using three inverters, each operates at 66. 7 percent efficiency further away from the knee of the efficiency curve. Three inverters provide an overload capability of 150% (since each of the inverters is operating at 2/3 load, each can accommodate 1/3 load increase or 50%). The synchronous inverter requires a power grid or separate frequency excitation source for operation and cannot be used with a "stand alone" system. Therefore, inverters of this type are not very suitable for remote site power systems.

3.2.2.3 Wind Turbine

In the cold climate of Barter Island, Alaska, lubrication and bearing life are a special consideration regardless of the wind converter selected. For this application two choices of wind converter size, as shown in Figure 3. 12, are most readily available: (1) The 2-3 KW size (four or five of these turbines are obtainable off the shelf). One of the considerations looking at small size turbines is the number of turbines required to produce the required power (10 KW). (2) The other choice is the family of four 8 KW turbines under development by DOE. Included in this group is an 8 KW turbine developed by U. S. Navy Civil Engineering which currently has over 3000 hours of test time. This brings the total for consideration to five. Three of the DOE turbines and the Navy turbine are expected to enter testing at Rocky Flats, Colorado in the summer of 1979. Within a year four of five different designs of 8 KW turbines should be available with test time in high wind and extreme cold conditions making it possible to project preliminary reliability figures to determine the degree of adaptability to the Barter Island climatic conditions.

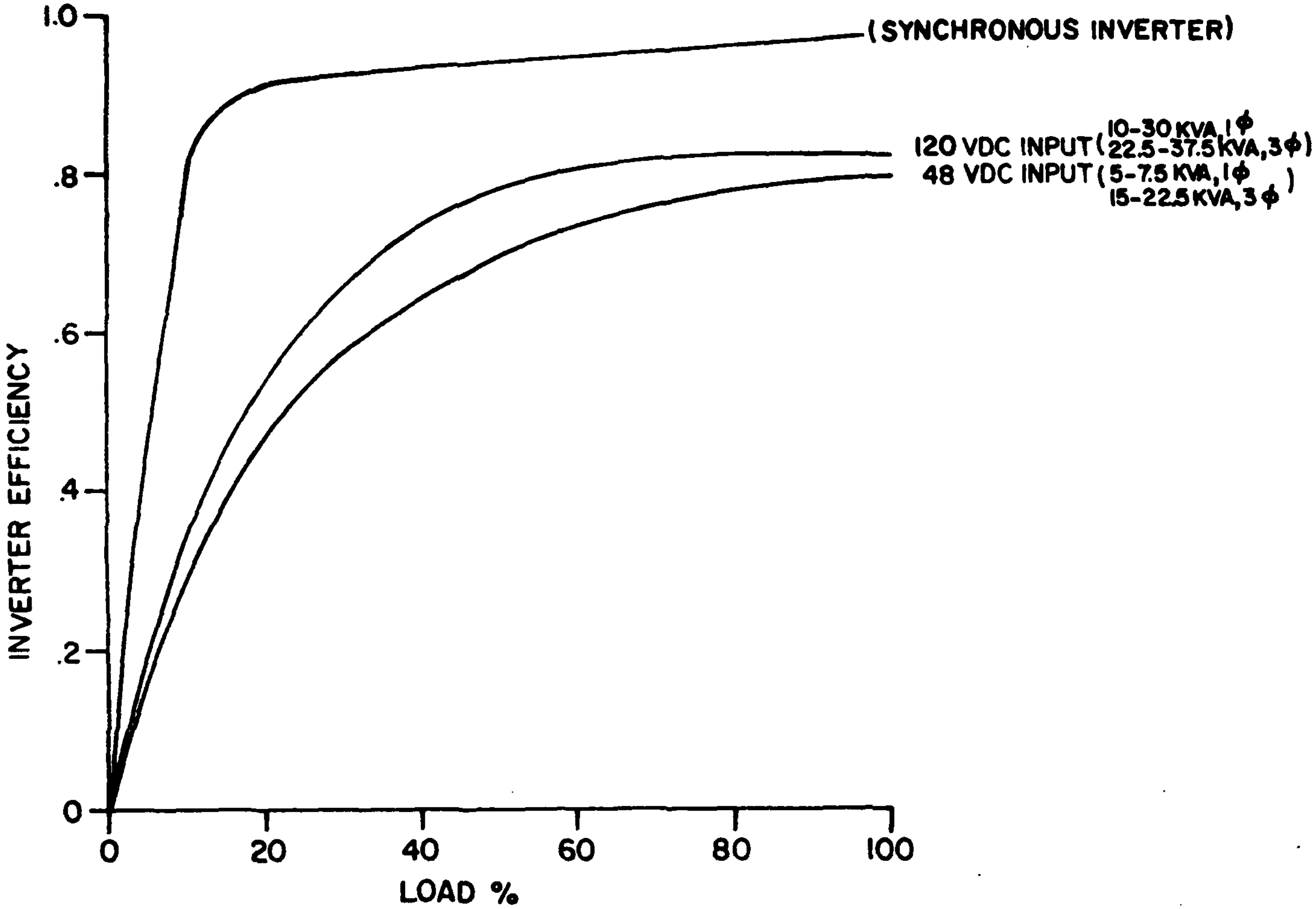


Figure 3.11 Inverter Load Interactions

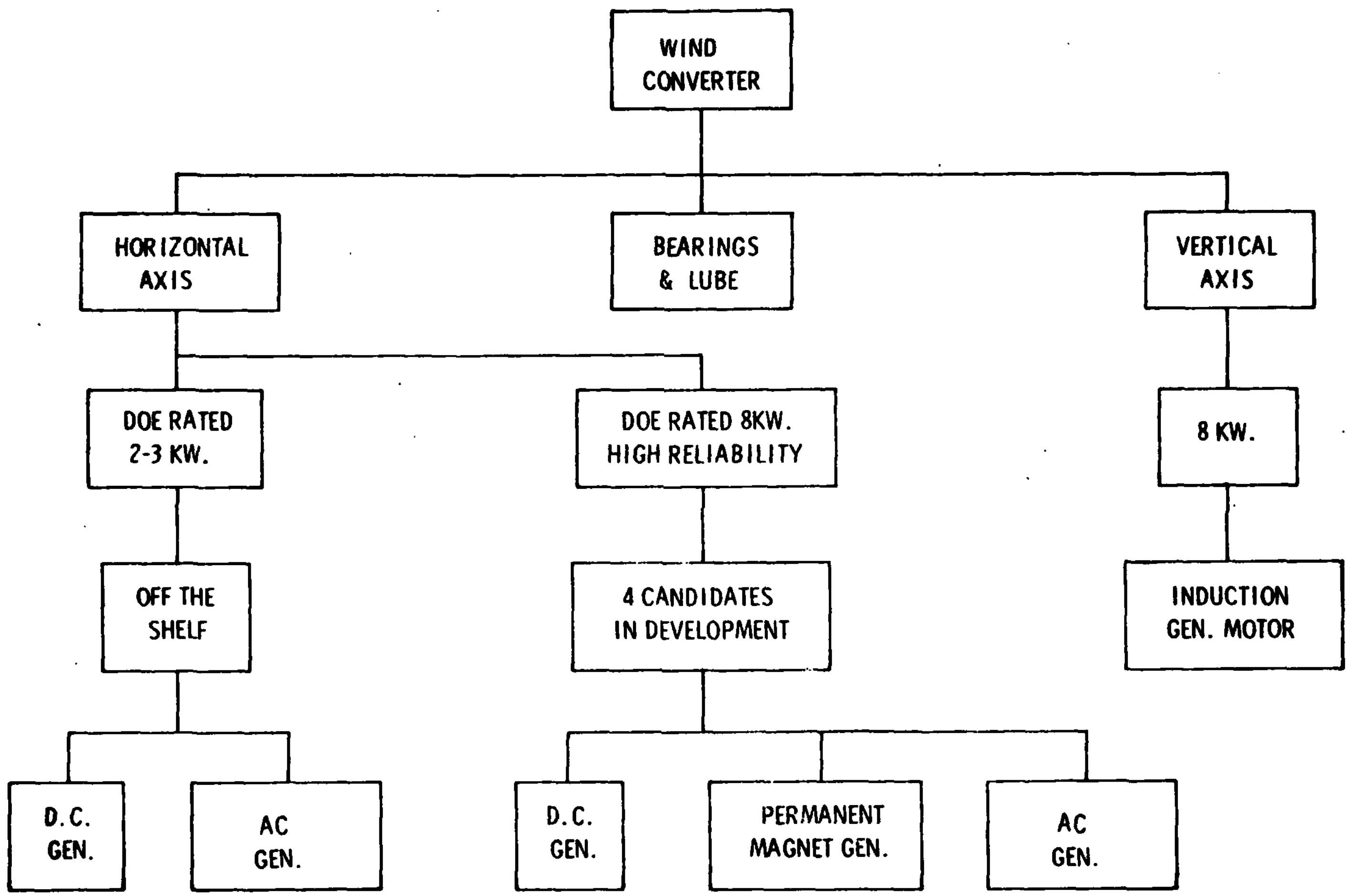


Figure 3.12 Wind Converter Trade Options

Within the 8 KW family another choice is available: (1) four of the candidates are horizontal axis machines, and (2) one candidate is a vertical axis machine. The instantaneous output of the vertical axis machine (C in Table 2.11) is lower than the horizontal axis machines in the 10-15 mph wind range which represents the monthly averaged wind variation at the Barter Island location. Special optimization techniques in the design of the curved blades could probably raise the output of the vertical machine at the lower wind speeds. It should also be noted that the vertical axis machine is not a self starter. The generator acts as a motor on initial start to bring the turbine up to operating rpm. The motor is activated when wind speed rises to the neighborhood of 7 or 8 mph and remains steady for 30-45 seconds.[20]

3.2.2.4 Tower

A 50-60 ft tower will probably place the rotor of a horizontal axis turbine sufficiently high in the ground boundary layer to capture most of the wind energy. Placing the tower away from clusters of buildings or other obstructions is helpful in obtaining more energy from the wind.

Two choices of tower construction, as shown in Figure 3.13, are available: (1) The guyed tower is lighter in weight and costs about half as much as a self-supporting tower to perform the same duty. The disadvantages of the guyed tower include maintenance associated with maintaining proper tension on the guy wires, pile foundation required to fasten guy wires to ground, birds and airplanes subject to additional hazard in flight because of guy wires. (2) The self-supporting tower overcomes the disadvantages of the guyed tower for increased cost and weight.

The foundation to support the tower can be constructed by drilling into the tundra, placing wood or steel pile in the hole, then pouring water in the hole and letting the water freeze. Creosote

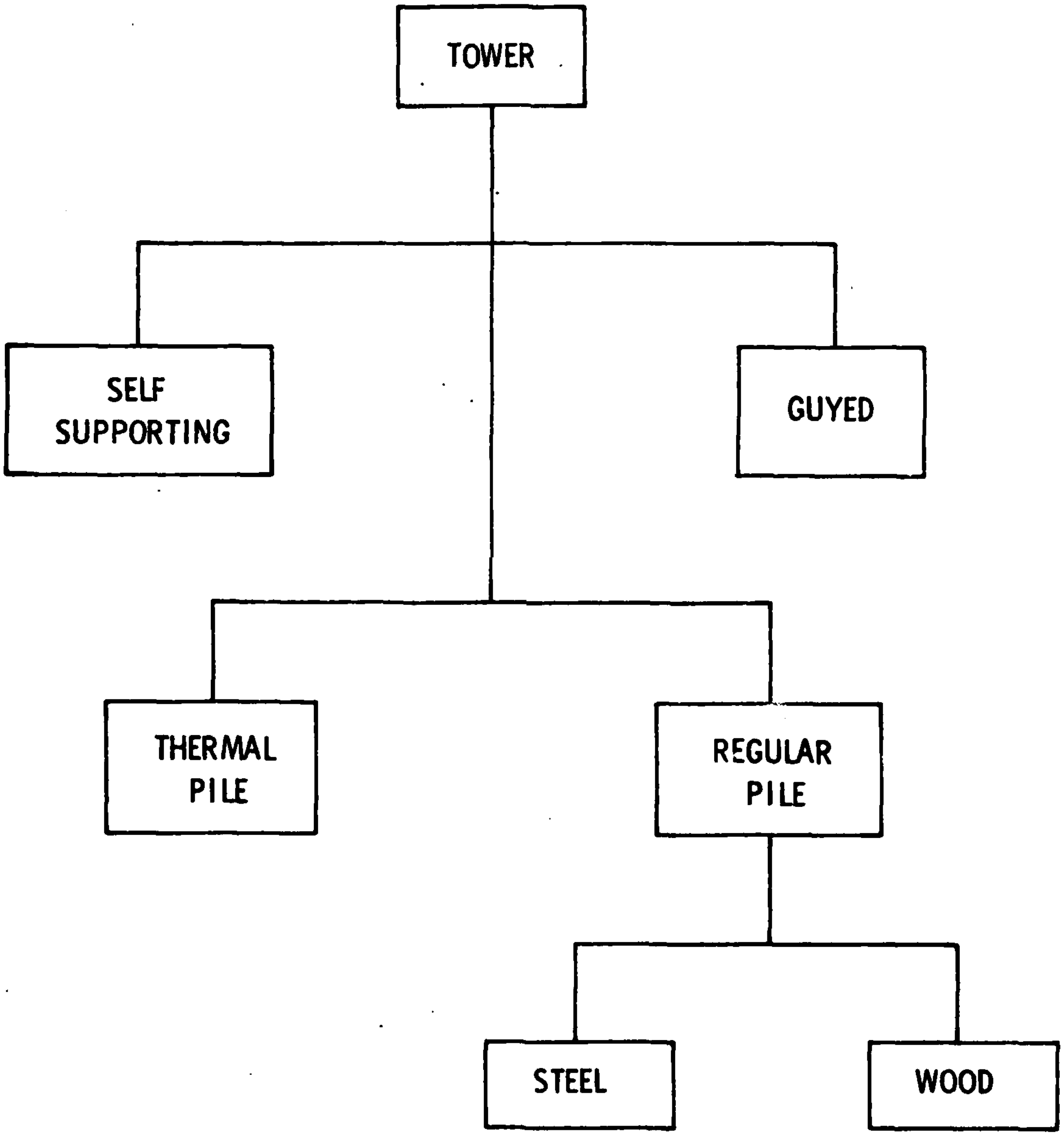


Figure 3.13 Tower Trade Options

treated wood pile is frequently used but steel pile is also available. Some steel pile have mechanical flare devices to provide additional support. In the event salt water infiltration is sufficient to cause the frozen pile foundation to thaw toward the end of the summer a thermal (refrigerated) pile is available. The thermal pile utilizes a gas vapor cycle to "supercool" the subsoil during winter sufficiently to prevent thawing in summer.

3.2.3 System Configuration and Control Functions

The system is easiest described by a series of simplified schematic representation which build upon one another so as to isolate particular functions or features. Figure 3.14 shows a simple system of two wind turbines supplying a DC load with battery energy storage. A DC output from the wind turbines is used so that they may be operated in parallel and avoid the synchronization problems that were discussed earlier. The DC output is also compatible with the battery since it is a DC device. Diodes are used to isolate the wind turbines from backward flow of current from the DC bus during low wind periods. Figure 3.15 shows the previous system with an inverter added to provide the required three phase AC output. The next Figure, 3.16, builds upon the previous system. A three phase transformer with delta connected primary windings has been added to filter harmonic frequencies from the AC output from the inverters. With these last two AC systems a control function requirement is introduced for operation into a power grid. The output frequency voltage and phase of the system must be controlled to be compatible with that of the power system. In Figure 3.17 provisions for charging the batteries from the power grid has been added. The charger is a simple transformer rectifier unit with a limited current and regulated voltage output. A switching function is introduced so that the inverter and output transformer are removed from the bus and grid respectively to prevent system instability and oscillation. The diodes in the wind turbine outputs isolate

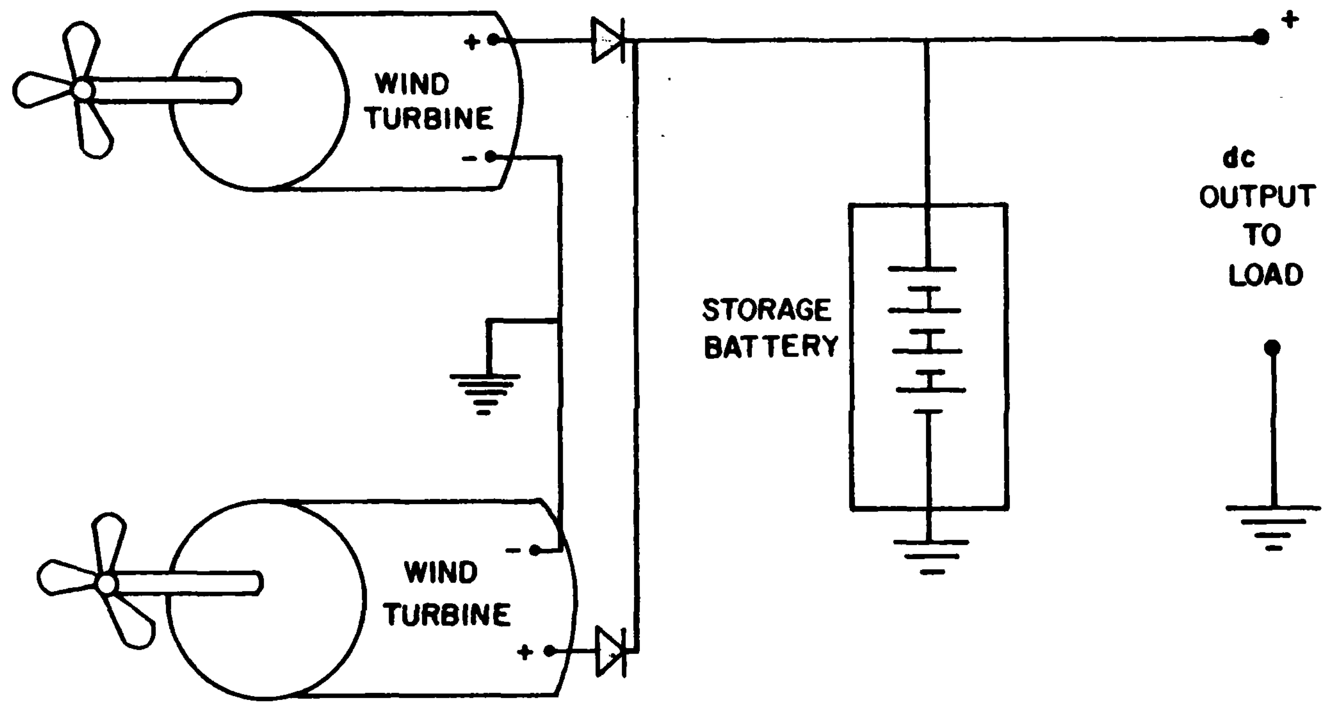


Figure 3.14 Wind Turbine/Energy Storage Power System with DC Output

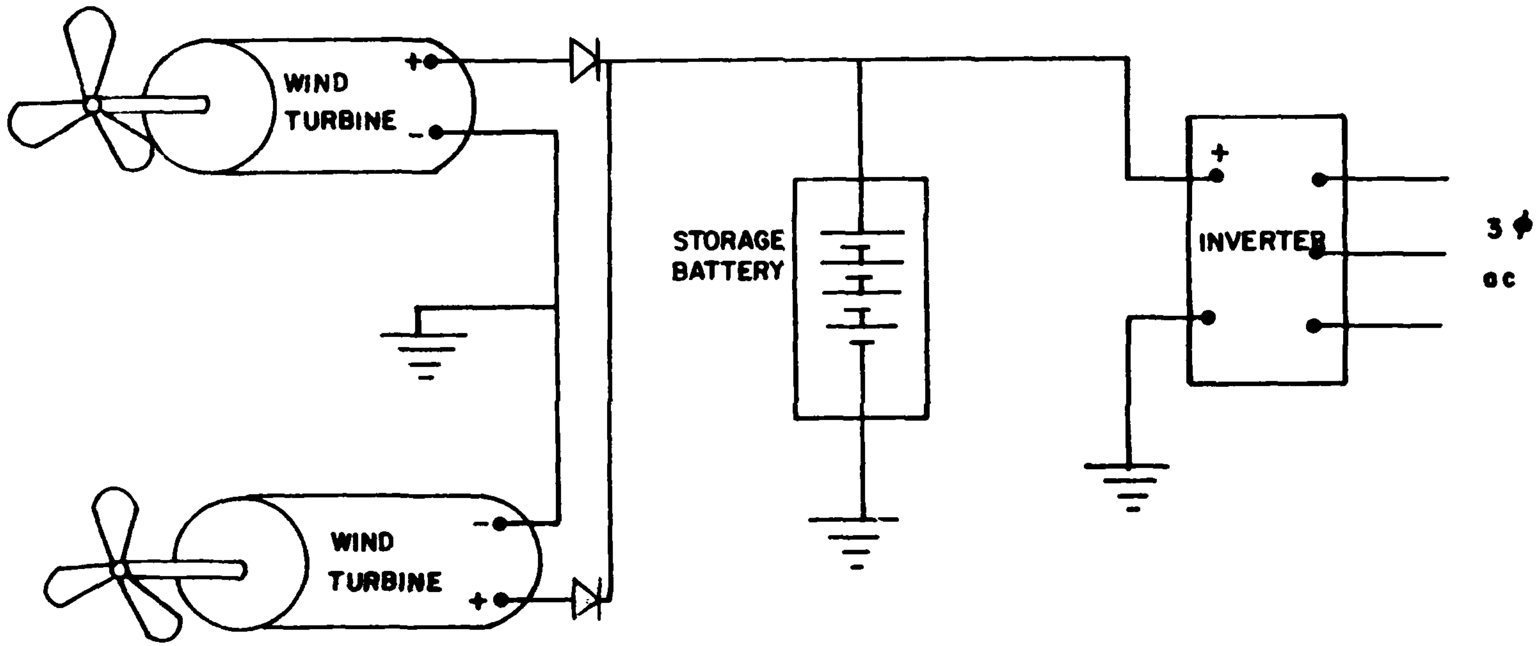


Figure 3.15 Wind Turbine/Energy Storage Power System with AC Output

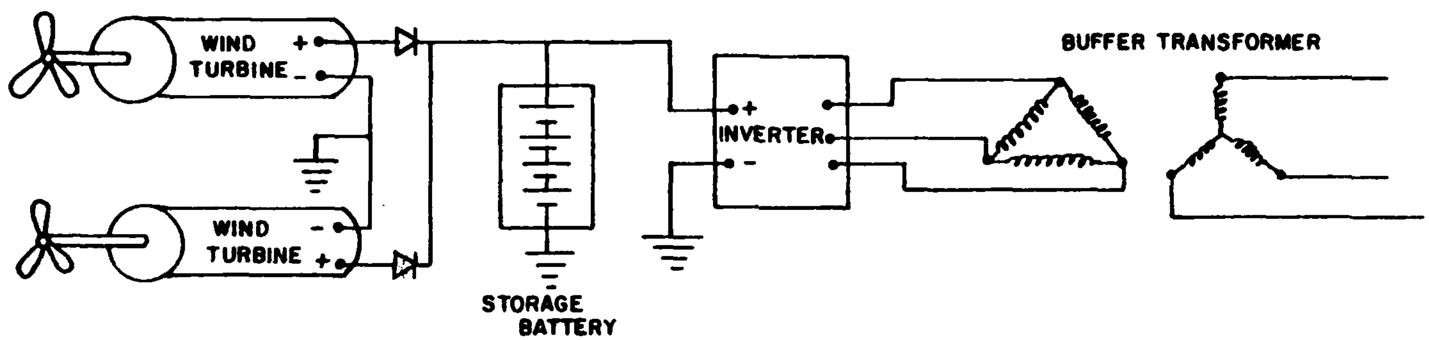


Figure 3.16 Improved Wind Turbine/Energy Storage Power System With AC Output

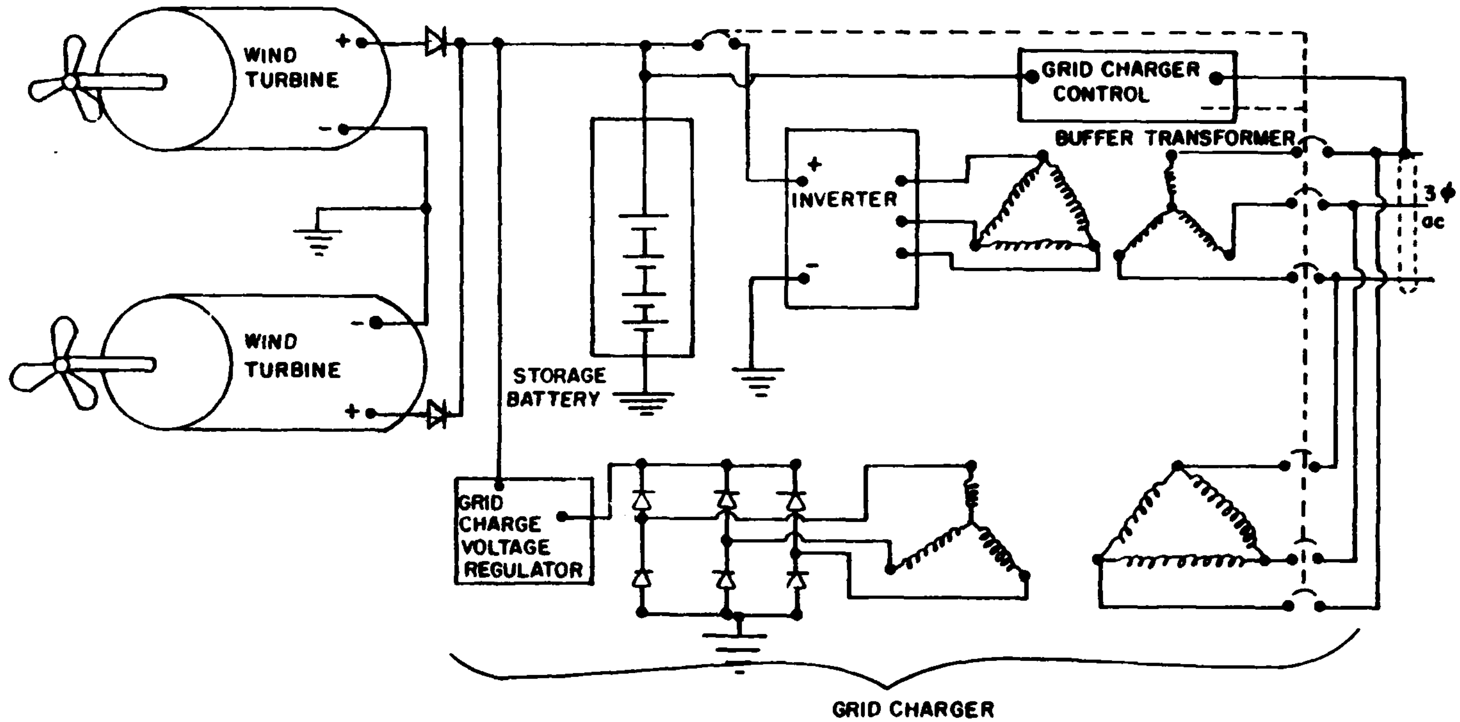


Figure 3.17 Improved Wind Turbine/Energy Storage Power System With AC Output and Capability for Charging Energy Storage from Power Grid

them from the grid charger and permit simultaneous charging from the grid and wind turbines when wind power is available. Figure 3.18 shows the addition of an auxiliary load to dissipate excess energy generated by the wind turbine during prolonged periods of high wind after the batteries have become fully charged. The preceding series of simplified schematic diagrams each introduced a new function leading up to the final system configuration shown in Figure 3.19. This figure shows the component redundancy and some of the control functions have been combined into common units. A redundant output transformer has been added to eliminate the possibility of a single point failure. This redundant transformer is switched into the circuit if the main transformer fails. The failed transformer must be switched out of the circuit. Parallel operation of the transformers is not recommended because slight variations in transformer characteristics due to manufacturing tolerances will result in unequal sharing of the load and possibly overload of one of the transformers.

3.2.4 Wind and Sun Correlation

The use of wind and sun energy in a hybrid system is attractive because of the negative seasonal correlation. Figure 3.20 shows the average wind speed at Barter Island to be highest during winter months while maximum hours of sunlight are experienced in the spring and summer months. Another advantage of the hybrid system is that maximum sunshine is normally the time of peak electrical demand. The Phase II system of this report can be easily converted to a hybrid system by simple addition of photovoltaic panels.

3.2.5 Collateral Design Issues

During the course of the design and system analysis, several areas required investigation to support the design and provide backup information. These areas were cost, reliability, maintainability and safety. The results and analyses relative to each of these areas of investigation are discussed individually.

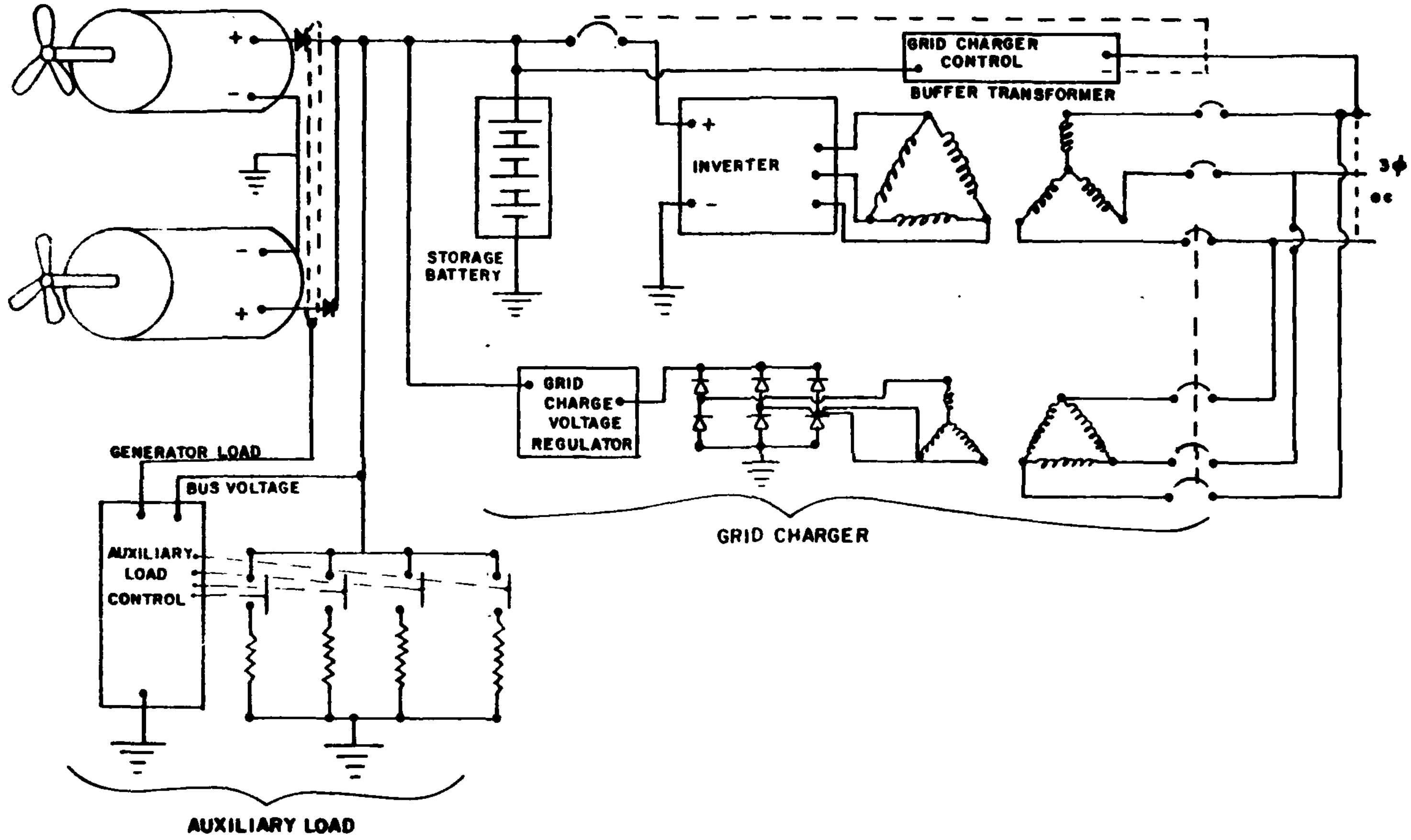


Figure 3.18 Improved Wind Turbine/Energy Storage Power System With AC and Capability for Charging Energy Storage from Power Grid and Auxiliary Load to Dissipate Excess Energy During Prolonged Periods of High Wind

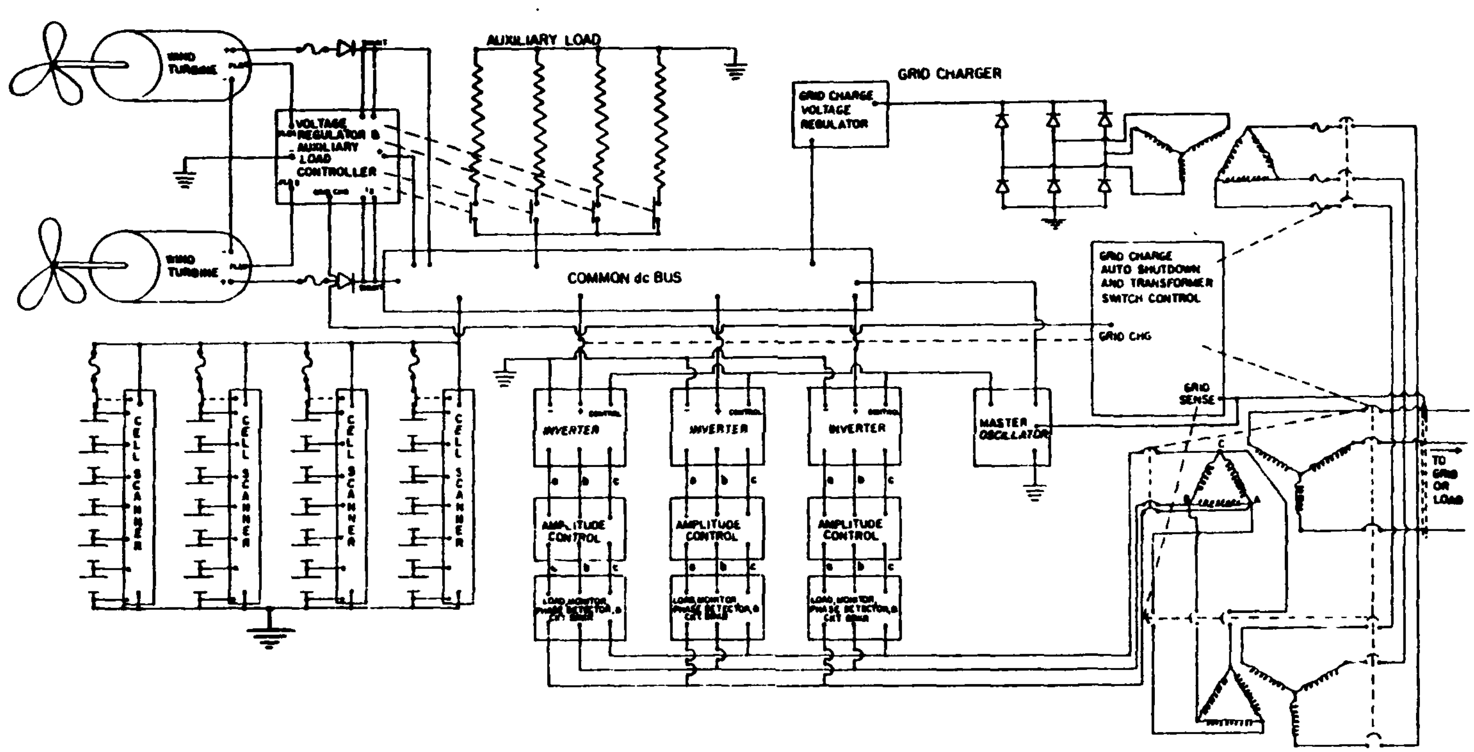


Figure 3.19 Final System Configuration

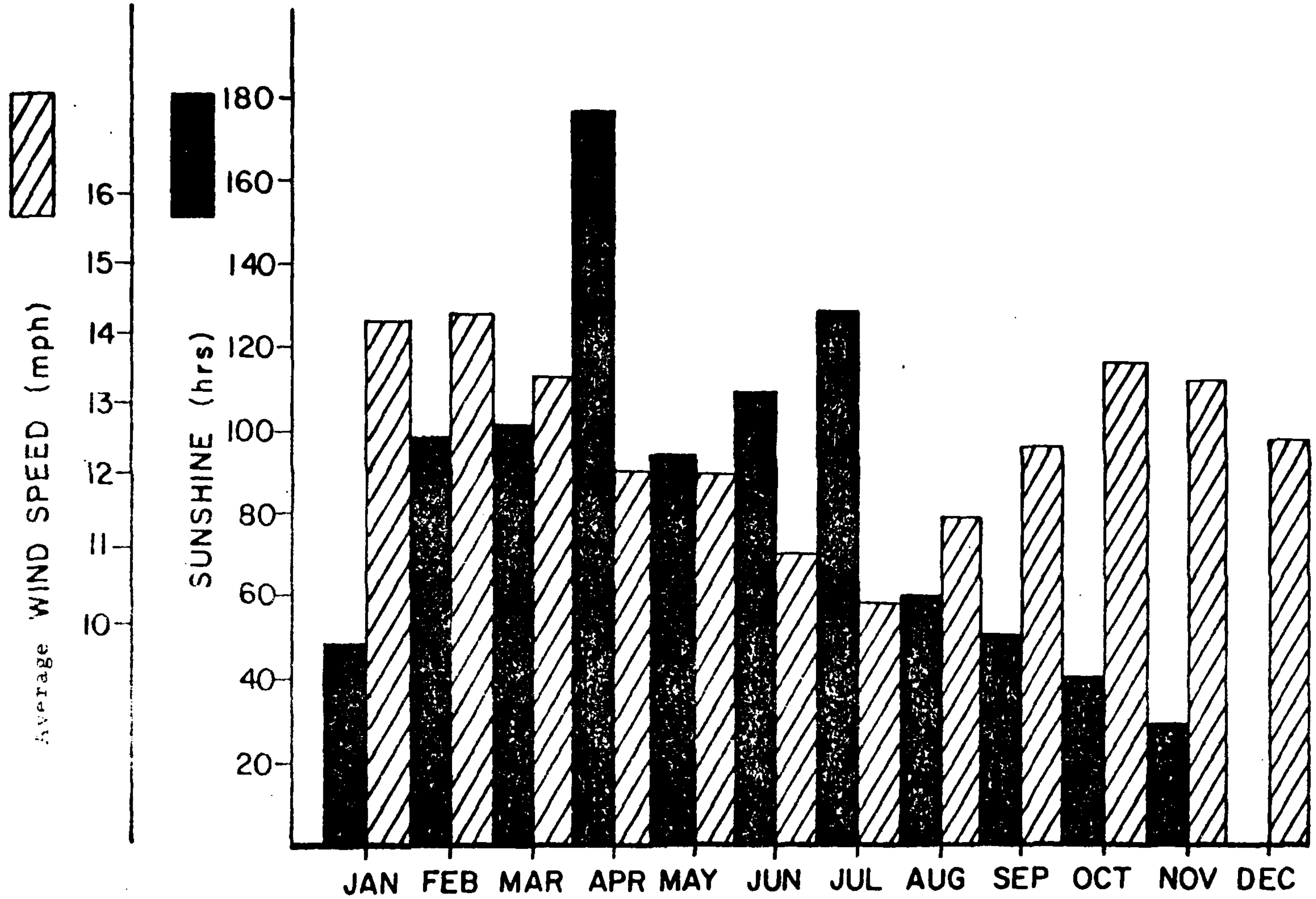


Figure 3.20 Sun and Wind Correlation Characteristics, Barter Island, Alaska

3.2.5.1 System Cost Analysis

The proposed wind energy/battery storage system cost was estimated for the Bar Main location. Also, a relative comparison of the cost of a 2 kilowatt module wind energy/battery system with that of a diesel system was completed for unattended power systems based on a 1977 General Electric study.[2]

3.2.5.1.1 Estimated system cost

Table 3.1 shows the projected system cost. The estimated wind turbine costs were obtained from manufacturers as being typical for the 8 kilowatt high reliability turbines. The tower costs represent either a guyed tower, lower cost, or a free-standing tower, higher cost. The particular tower used depends on the dynamic design analysis. The installation and freight costs include the cost of transportation and installation of 1) the wind turbines, 2) the towers, and 3) the storage system. The battery storage cost was based on $150 per kilowatt hour and 400 kilowatt hours of battery capacity. The necessary battery capacity was determined in Section 3.2.2.1. The desired storage capacity was 240 kilowatt hours, the inverter efficiency used was 80% and the depth of discharge was estimated at 75%. The estimated power conditioning and control costs are based on three inverters, a grid charger, and the control units. The control units include the switching control and voltage regulator units necessary for use with the wind turbines.

The estimated cost of system integration is the largest single cost in the system cost analysis and is variable. It is estimated that it would take approximately one and one half to three man years at $60,000 per man year plus travel and supplies to integrate the system. Some design would be required in that control units such as voltage regulators and switching controls do not exist in sizes necessary for this system and are unique to the particular system design. Battery chargers exist but compatibility will have to be evaluated. The range of

TABLE 3.1

SYSTEM COST PROJECTIONS
(in thousands of dollars)

Wind Converter System (2 Converters)	20-50
Tower (2)	4-8
Installation and Freight	20-40
Battery Storage	60
Power Conditioning and Control 3 Inverters + Charger + Control Units	60
Systems Integration (1-1/2 - 3) MY @ $60K/yr + Travel and Supplies)	100-200
Maintenance (1st year) (3 days/mo incl. travel time + 7 days/yr (2 men) + travel)	55
Pile Drilling Rig (Rental)	0-50
Core Test	0-30
TOTAL	264-533

$100,000 to $200,000 is an estimate of cost to design and integrate the system prior to installation.

The estimated first year maintenance cost of $55,000 includes three days a month to inspect and perform minor maintenance at the Bar Main site (one day travel to the site, one day at the site, and one day travel back). Also, an annual maintenance of seven days would be required which allows for five days of major maintenance at the site and two days travel to and from the site. Since large components may have to be handled it is estimated that two persons will be required to perform the maintenance.

Based on discussions with personnel installing wind turbines in Alaska it may be necessary to transport a drilling rig and pile driver to the Bar Main site. The estimated cost of the pile driver includes transportation of the drilling rig and the installation of the piles and depends on availability of a drilling rig on Barter Island. At present there is no drilling rig on Barter Island. The core test is a soil sample test which is used to determine the best locations for the wind tower foundations. There is a potential problem of salt water infiltration on islands such as Barter Island. If core tests have already been performed at Bar Main these tests may not be necessary.

The total system cost is estimated to range between $250,000.00 to $500,000.00. These figures could be significantly reduced if initial demonstration of the system is completed at a test site that is not remotely located.

3.2.5.1.2 Cost comparison of wind energy and diesel power systems

A cost comparison of wind energy/battery versus diesel systems was completed based on a 1977 General Electric study of two kilowatt unattended power systems.[2] The study was concerned with replacing the existing DEWLINE system with the Northern

Air Surveillance Distant Early Warning System (NASS). The DEWLINE system consists of 31 search radar systems which span a 3600 mile chain along the northern border of North America. The proposed NASS system will require 85 sites. Diesel systems were compared with wind/battery systems and isotope fueled systems for two kilowatt unattended power systems. Based on existing wind data only 80% of the 85 sites (68 sites) were suitable for wind/battery systems. Thus in the comparison the remaining 20% of the sites (17 sites) in the wind/battery systems were, in fact, diesel systems.

The development phase provided for the design, development, fabrication and qualification of a prototype unit. With diesels this includes technology development such as those that may be needed to extend maintenance intervals beyond three months. With the diesels normal maintenance activities occur at 3 month intervals and consist of starting each unit to check operability, replacing fuel and oil filters, replenishing fuel and oil supplies and a general inspection. Major concerns are lubricating oil degradation and fuel injector fouling. Carbon fouling of the injectors is fairly common especially where the engines are operating continuously at 50 to 60% of rated load. The state-of-the-art diesels considered in the study require major overhaul periodically and is such that the overhaul, from the practical standpoint, must be accomplished at a central repair depot. This means that a spare unit must be transported in to replace the used unit and a major overhaul is estimated to be needed every two years. The study concluded that (1) it is doubtful that diesel system maintenance will ever exceed one year, (2) fuel must be resupplied annually, and (3) fuel weight along with replacement diesel for overhaul would require significant helicopter capability for maintenance of each site.

In the comparison of the diesel system and the wind/battery system with other systems diesels ranked first and wind/battery second and listed the following advantages and disadvantages for the systems:

A) Diesel System

1. Diesel systems are demonstrated systems with modest, low risk development required in the area of controls and switching.

2. The economics are well defined.

3. The systems are competitive for 10 and 20 year missions from life cycle cost or levelized annual cost.

4. Helicopter rental charges dominate the cost.

5. There is a potential of up to one year maintenance free but not beyond.

B) Wind/Battery

1. Wind/battery systems would conserve up to 70% of the fossil fuel cost of diesel systems.

2. No technical breakthrough would be required.

3. Precise wind data is not available and detailed data collection and analysis would be required.

4. The overall system risk would be increased over that with the diesel system.

5. System life cycle costs are competitive with the diesel systems whereas the levelized annual costs are higher.

6. System costs are dominated by initial site preparation.

The relative cost comparison is shown in Table 3.2 with the reference or baseline cost being the diesel system. The comparison is based on a 10 year operating life for 2 kilowatt systems. It is interesting to note that the wind/battery system, based on 1977 costs, is only approximately 13% greater than that of the diesel systems. The fuel costs for the wind/battery systems occur due to the fact that 20% of the sites were not suitable for wind/battery systems. The comparison does not include escalating fuel costs which would tend to reduce the differences between the systems. Since the proposed system could be built up of two kilowatt modules the relative cost comparison is somewhat realistic.

TABLE 3.2

REMOTE COST COMPARISON OF WIND/BATTERY REMOTE SITE SYSTEM WITH DIESEL SYSTEM (10 Yr. Operating Life)*

	Diesel	Wind/Battery**
Development	0.0514	0.1052
Demonstration	0.0525	0.1098
Production	0.1366	0.2629
Site Preparation	0.1388	0.3609
Installation	0.0106	0.0262
Fuel	0.5343	0.2162
Other Operation & Maintenance	0.0758	0.0485
	1.0000	1.1297

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* Based on 2 KW(e) Unattended Power System Study by G. E. (1977). (Northern Air Surveillance Distant Early Warning System)

** Assumes 20% of sites diesel.

3.2.5.2 Reliability Analysis

A preliminary reliability analysis was conducted on the system shown in Figure 3.19. A diagram of the model is shown in Figure 3.21. The reliability of each of the components is shown in Table 3.3. The equivalent parallel reliabilities for the components as shown in Figure 3.21 are also tabulated in Table 3.3. The equivalent parallel reliabilities were calculated by the formula:[49]

$$R_{EP} = 1 - \prod_{i=1}^{n} (1-R_i) \qquad (3.12)$$

where

R_{EP} is the equivalent parallel reliability

R_i is the individual component reliability

n is the number of components in parallel.

The equivalent series reliability was then calculated using the model shown in Figure 3.21 and the expression:[49]

$$R_S = \prod_{j=1}^{n} R_j \qquad (3.13)$$

where

R_S is the series reliability

R_j is the equivalent parallel reliability of each of the series elements

h is the number of series elements.

In the system diagram, (Figure 3.19) the batteries are electrically connected in parallel with the wind turbines but are shown in series in Figure 3.21 for calculation system reliability because loss of the batteries would fail the system. The equivalent system reliability was calculated to be 0.9497 to supply the design rated power. The grid charging input was ignored in these calculations. The numbers used in

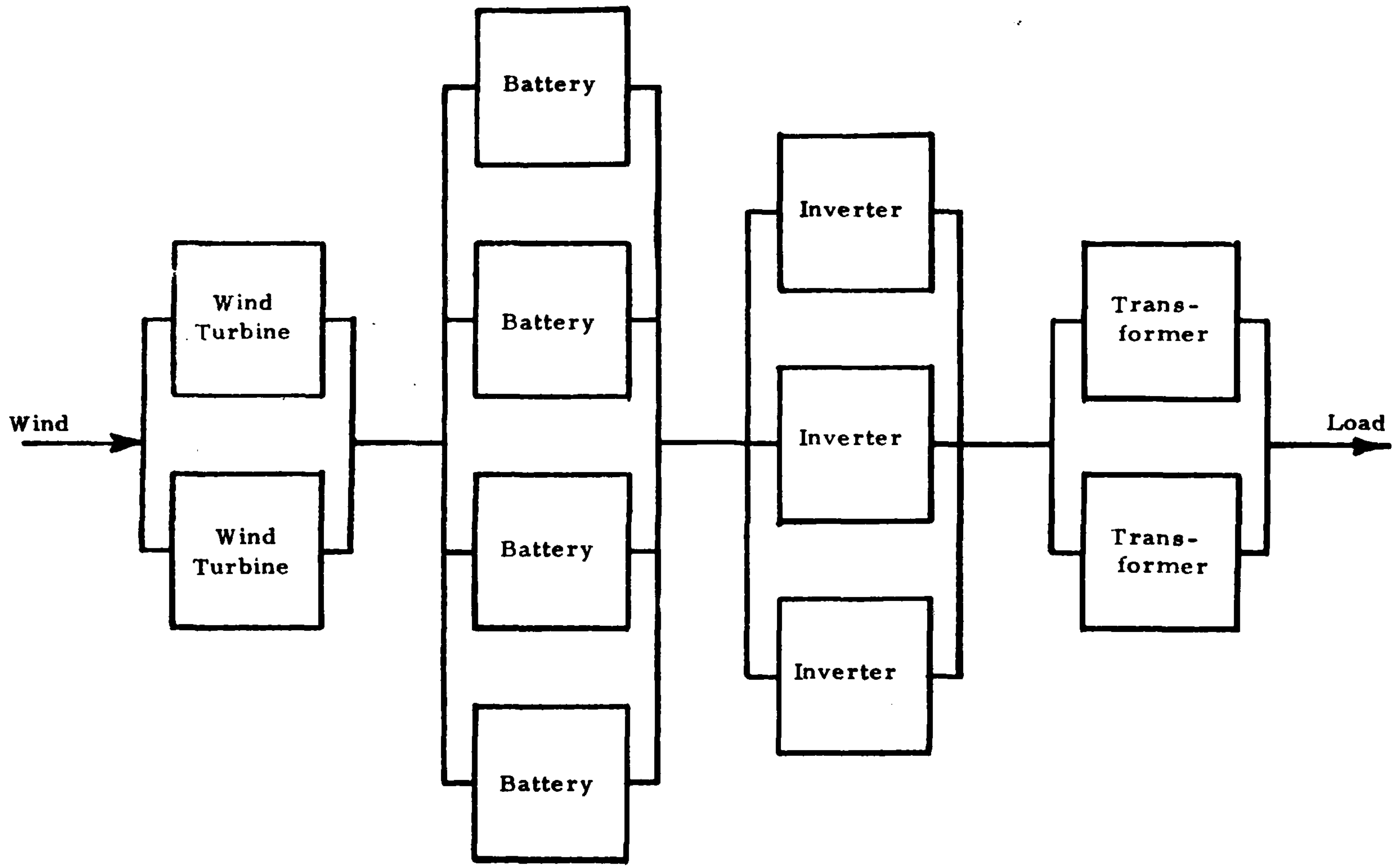

Figure 3.21 Reliability Model

TABLE 3.3

COMPONENT RELIABILITIES

Component Name	Single Component Reliability	Equivalent Parallel Reliability
Wind Turbine, Ref. 2	0.9500	0.9975
Inverter, Ref. 2	0.9800	0.9999
Battery, Ref. 2	0.9500	0.9999
Transformer, Ref. 3	0.998	0.9999

this calculation were the single component reliability of the wind turbine, the equivalent parallel reliability of two inverters, the equivalent reliability of three parallel battery strings, and the equivalent parallel reliability of two transformers.

A degraded mode reliability was calculated to be 0.9973. This is the reliability of the system to supply some electrical power but perhaps at a reduced level from the design level. The equivalent parallel reliabilities from Table 3.3 were used in the above calculations. As before, the grid charging input was ignored in the calculation.

The preceding reliability analysis is based on values taken from the literature as being representative of typical components. An experimental or prototype demonstration program should provide for full documentation of the reliability performance.

3.2.5.3 Maintainability Considerations

The contract work statement specified a maintenance cycle of up to one week per year; however, during the analysis, several other maintenance and maintenance related considerations surfaced. The anticipated use of these power systems is in remote locations which are not usually manned or frequently visited; therefore, the units should be designed for zero unscheduled maintenance over the design life. It is desirable that the life be as long as possible; however, a component design life of at least three years (26,298 hours mean time between failure) seems reasonable. The propeller, gear box, and generator are mounted on a tower which are subjected to a hostile environment and there should be no required maintenance of these items over the design life. Lubrication and bearings should be of high quality, long life design. No adjustments or physical examinations of these components should be required. The entire system should include self diagnostic and checking equipment such as a mini-computer to identify and isolate failed or degraded components. The output should provide the maintenance teams with information on the components to be replaced so that extensive check out or diagnostic procedures are not required. Since the system is likely to be a primary power source, it is desirable that maintenance be performed without total system shutdown. In the event of failure, the components should be able to be replaced on a module or submodule basis without complete system teardown or overhaul. For example an entire wind turbine might be replaced or a printed circuit card in the inverter or a single cell in the battery string. The maintenance and component/module replacement function should be achievable by a two-person specialist team in accordance with existing human factors standards using conventional tools and instruments. Lastly, this is a new system and accurate maintenance records should be made during the experimental or prototype demonstration to verify the maintenance requirements, frequency, and cost.

3.2.5.4 Safety Considerations

The safety considerations fall into four general categories; location, human factors, environmental factors, and system. Each of these categories is discussed below. There are some items of overlap between the human and environmental factors areas as noted below.

3.2.5.4.1 Location Considerations

The primary considerations in this area are associated with the wind turbine systems. If some of the rotating parts such as a propeller blade should break or loosen, would the falling part be likely to do damage to other nearby equipment or constitute a hazard to personnel? The uppermost point of the rotating propeller will probably be 100 to 150 feet above the ground so aircraft avoidance lighting needs to be considered. Weather data indicates that fog is likely to occur frequently at the Bar Main location. If the tower is guyed, wildlife and aircraft collisions need to be considered. In the event of a tower failure and collapse, damage to personnel and objects on the ground must be considered.

3.2.5.4.2 Human and Environmental Factors

The system produces moderately high power levels and contains a large amount of stored energy. Voltages are high enough to be lethal. Under maximum power conditions, batteries can typically deliver about 20 times its rated load. For a four parallel string battery system as previously described each string would contain 100 kilowatt hours of energy and have a nominal rating of 8.33 kilowatts. Such a battery could deliver 166.7 kilowatts or 3333 amperes at 50 volts. Short circuit currents could exceed the maximum power value by a factor of 2 to 5. The foregoing observations dictate careful attention to elimination of exposed electrical terminals since maintenance personnel will be working with and around the components. The possibility of inadvertent short circuits of the battery must also be eliminated. The batteries can also present some other potential hazards if not adequately provided for in the system design. The batteries contain strong concentrations of sulfuric acid which could be spilled during handling and cause damage to adjacent equipment or injury to personnel. In many of the sealed batteries, the electrolyte is immobilized and cannot be spilled. The batteries also emit vapors during charging and overcharging. These vapors may be corrosive (sulfuric acid mist) or explosive (hydrogen) or toxic, i.e., trace amounts of arsine (A_sH_3) or stibine (SbH_3) can be generated. These vapor emission problems can usually be avoided by adequate ventilation; however, ignition sources such as sparks from tools, switching contacts, and smoking materials should be eliminated around the batteries.

3.2.5.4.3 System Considerations

A failure or fault, if it should occur in the wind power system, should not cause serious or irreparable damage to the load. When the wind power system is operated into a power grid, it should not fail in such a manner that its' failure produces a failure of the power grid into which it is operating. Similarly, since the wind power system represents a considerable cost, a fault of the load or power grid into which it is operating should not excessively damage or destroy the wind power system.

3.2.6 Fault Analysis

The conceptual system of Figure 3.19 was analyzed for behavior in the event of a fault. Two types of faults, short circuits and open circuits, were considered. Only single component failures or faults were considered (i.e., after one fault had occurred no further faults were considered). Failures of the following components were considered:

- Wind Turbine Generator
- Grid Battery Charges
- Buffer Transformer
- Inverter
- Battery

A failure of one of the wind turbine generators would reduce the total amount of wind energy converted by 50 percent. The outputs are isolated from each other and the system by diodes so no effect other than reduced power output would be noted. The voltage regulator must be able to control under both open and short circuit faults and not become unstable or destroy itself.

A failure of the grid battery charger only results in the loss of that capability. An open circuit results only in the loss of the grid charging capability. The grid battery charger is protected by circuit breakers against short circuits at the input to the transformer rectifier. In the event of a short circuit, the circuit breakers open the circuit and the net effect is the loss of grid charging capability.

The buffer transformer is the interface between the load/grid and the wind power system. The net effect of either an open or short circuit failure of the transformer would be a switch to the back-up transformer. An open circuit would be sensed as a no load or severely unbalanced load and the grid condition would be sensed to see if the fault is on the grid or in the transformer. If the fault is on the grid, the transformer output circuit breakers would open due to load unbalance or the system would sit idle if all the phases were simultaneously open. If the fault is in the transformer, an immediate switch would be made to the backup or redundant transformer. A short circuit would behave essentially the same way as an open circuit in that it would cause the circuit breakers to open and an automatic switch to the redundant transformer would occur.

An inverter failure would be of little harm since the two remaining can carry the full load. They are also protected by circuit breakers in the event of a short circuit or heavily unbalanced load situation and would be automatically removed from the circuit. An open circuit would have very little, if any, impact.

The battery is similar to the inverter. An open circuit of any cell would remove that string from the circuit and since the total battery capacity is oversized by 33% and there are four parallel strings the remaining three would carry the load. The situation of real concern is an internal short circuit of an individual cell. In this case the cell could destroy itself and perhaps those around it or start a fire. This is one of the main functions of the scanner units shown in Figure 3.19. The scanner would detect a cell with a low voltage and alarm of a weak cell. If the cell voltage dropped to a very low voltage its battery string would be automatically removed from the circuit.

3.2.7 Design Issues Requiring Resolution

The design study and analysis conducted under this phase of the program identified four design issues, three of which are interrelated, that require resolution before final design of any prototype system. These four issues are discussed below.

3.2.7.1 Design Power Level

The Phase I work statement specified a nominal 10 kilowatt system (i.e., a 10 KW load) and the Phase II work statement specified the use of two of the nominal 8 kilowatt wind turbines of type similar to those being developed under the DOE compilation. Analysis of Figures 3.6, 3.7, and 3.10, shows that to expect a system with a continuous 10 kilowatt load to be supported by two nominal 8 kilowatt turbines is optimistic at the Barter Island location. The average wind speed is below the design speed where the nominally rated 8 kilowatts is obtained. The design power level could be reduced or the number of wind turbines could be increased. The foregoing discussion serves to re-emphasize that careful attention must be given to the wind speed distribution at the location of intended use (i.e., a system designed to produce a given power output at one location may produce significantly more or less power when moved to a different location).

3.2.7.2 Design Wind Speed

The wind turbine and storage system can be designed to operate at maximum efficiency at one of several wind velocities. Three monthly average wind velocities that are candidates for the design wind speed are: (1) the minimum monthly average wind velocity, (2) the mean monthly average wind velocity, and (3) the maximum monthly average wind velocity.

If the system is designed to operate most efficiently at the minimum monthly average wind velocity minimum power grid supplement will be required; however, in the high wind winter months energy will need to be dissipated in an auxiliary load such as a heating resistor bank.

If the mean monthly average wind velocity is selected as the design wind speed some supplement will be required from the power grid, primarily during the summer months, and during winter months some energy will need to be dissipated in an auxiliary load.

Selecting the maximum average monthly wind velocity as the design speed reduces the need for auxiliary load almost completely, but supplement from the power grid is required except during the high wind winter months.

3.2.7.3 Storage Capacity

In view of the above discussions relative to design output power, it seems advisable to reassess the energy storage capacity requirement if a decision is made to reduce the output power requirement. For example, if the design output power should be revised to be 5 kilowatts, then, perhaps, 120 kilowatt hours of energy storage are needed in lieu of the 240 kilowatt hours originally specified.

3.2.7.4 Battery Options

The available battery options have been previously discussed in Section 3.2.2.1 and are reiterated in Table 3.4 to facilitate comparison. From preceding discussions of design features, maintenance, and safety the sealed battery is clearly the best choice and mature technology is available; however, cell sizes in the capacity range of interest are not available. The other options represent compromises but proven hardware is available in the size range of interest. In order to select a "best" type from these other options, life requirements (goals), maximum permissible maintenance frequency, and allowable venting limits must be specified.

TABLE 3.4
BATTERY OPTIONS

- SEALED
  - DEVELOPMENT REQUIRED FOR LARGE CAPACITY SYSTEM
  - MAY BE SATISFACTORY FOR SCALED DOWN SYSTEM

- AUTOMOTIVE
  - CHEAP/AVAILABLE
  - LIFE PROBLEM
  - WATER USE IN SOME CASES
  - VENT REQUIRED

- INDUSTRIAL
  - WATER USE
  - EFFICIENCY
  - VENT REQUIRED

- STAND BY
  - LIFE PROBLEM (# CYCLES @ DEEP DSCHG)
  - VENT REQUIREMENT

3.2.8 System Design Checklist

A checklist of important items to be considered in the design of a wind energy storage system was formulated. The checklist, Tables 3.5 to 3.9, considers the complete system and then the individual components of the system, i.e. wind energy converter, tower, storage system and power conditioning and system control. Although the particular application is at Bar Main, Alaska, the checklist should be applicable for any location. The checklist reflects items which are considered important during the design of the complete system and indicates areas which should be considered, where applicable, before a procurement is issued.

3.2.8.1 System

Since modularity is a major consideration for the proposed remote site wind-energy-storage-system the compatibility and control of the interlocking modules are important to the total system performance. The total system design checklist is shown in Table 3.5.

Item I in Table 3.5 describes the proposed system for Bar Main. It consists of two wind turbines, a battery storage system, and a power conditioning and control system. The power conditioning system should be such as to insure compatibility of the power output with the grid or with the load dependent on whether the system is to be remote site or connected to a grid. The overall control system must control the overall system operation and be stable over the operating range of the system.

Item II gives the location of the site and is essential to the system design. The weather information can be obtained from the National Climatic Center and may have a serious influence on the system design as well as the system components.

The modular concept, Item III, is important from the standpoint of transportability, interchangeability, and realibility.

TABLE 3.5

SYSTEM DESIGN CHECKLIST

I. System Description

1. Two Wind Turbines
2. Battery Storage
3. Power Conditioning
4. System Control
5. Power Grid Compatible

II. Location

1. Bar Main located at Barter Island, Alaska

III. Modular Concept

1. Sufficient Redundancy to Eliminate Single Point Failure
2. Trade Off Study

IV. Reliability

1. Measurement Method
2. Levels Required

V. Maintainability

1 1. Ease of Maintenance

2. Frequency of Maintenance
   - A. System Check
   - B. Battery Water
   - C. Component Replacement

VI. Life, Cost, and Lift Cycle Cost Analysis

1. Expected Life for System
2. Durability Parameter Trade Off
3. Development Costs
4. Acquisition Cost Including Installation
5. Life Cycle Cost (including replacements, consumables, & maintenance)

TABLE 3.5 (continued)

VII. Environmental Parameters

1. Operating Temperature Range
2. Maximum Wind Velocity
3. Maximum Operational Gust Levels
4. Shock Levels
5. Humidity
6. Salt Fog
7. Sand and Dust
8. Fungus
9. Vibration Levels
10. Corrosion Resistance Characteristics
11. Explosive Vapors
12. Corrosive Vapors
13. Icing Levels
14. Toxic Vapors
15. Acoustic Noise
16. Maximum Altitude, Rate of Climb, Rate of Descent during Air Transport
17. Lightning Arrestor Requirements

VIII. System Size Criteria

1. Dimensions of Each Component
2. Weight of Each Component
3. Volume of Each Component

IX. Air Transportability

1. All Components Air Transportable IAW Governing AF Regulations

X. System Safety

1. Safety Requirements Specified in Governing AF Regulations Will Be Met

Sufficient redundancy in the system is necessary to eliminate single point failures. Since most remote sites are in a fairly hostile environment it is advantageous to design so that degraded amounts of power are provided in event of a component failure.

Reliability and maintainability are included in Items IV and V respectively. Our estimate of reliability indicates a reliability of 95% to supply full rated power and 99% to supply degraded amounts of power are reasonable goals. The method of measuring reliability should be specified. To that end failure criteria should be defined and minimum acceptable level of degraded operation should be specified. The system should be easy to maintain and frequency of maintenance should be minimum. Ease of maintenance includes the use of standard tools and accessibility of components. For example one would not want to climb a wind converter tower at $-50^{\circ}F$ or in high wind to work on a component. If there is a problem, it would be desirable to replace a component or a submodule. In event of a battery failure, it is desirable to change a small battery group rather than an entire battery string. It is also desirable to be able to perform maintenance operations without shutting the entire system down.

Item VI covers the life, cost, and life-cycle cost analyses. The system lifetime, operational life, storage life, and calendar life must be defined. During the life specification and analysis durability parameters must be identified to measure life and conduct tradeoff analyses. Cost information needs to be developed for all phases of the program including development, initial acquisition, and total life-cycle costs so that the payoff can be accurately assessed. Furthermore, these costs must all be referenced to the same standard baseline and inflation rate.

Item VII relates to environmental parameters that the system may see during its lifetime. Some are not applicable to all components but the designer or person specifying the system and the components should make a conscious decision to ignore these particular items. For example the maximum altitude, rate of climb, and rate of descent during air transport relate to the breathing effect of batteries through their vents.

Item VIII covers the component sizes so that reasonable size pieces result for transport, assembly, maintenance, and ultimately removal. The sizes must be considered in light of personnel and/or special equipment requirements. Items IX and X provide for the use of air transportability and safety requirements that are compatible with existing Air Force standards.

3.2.8.2 Component/Subsystem

The design checklists relating to the components and/or subsystems are broken into the four categories discussed below.

3.2.8.2.1 Wind converter

The wind converter design check list is shown in Figure 3.6. In specifying the design wind speed for the system consideration should be given to the amount of power required from the power grid since this puts a demand on the central power system at the remote site. The conservative approach is to select the minimum monthly average wind velocity as the design point since this requires minimum power from the grid and supplies excess power in winter that can be dissipated for building heat.

If an efficiency goal is specified it should be set at or slightly above the best efficiency predicted in the 8 KW family of wind turbines. Since this is a goal and not a requirement, the system contractor can use this as a measure of his performance for his own guidance.

TABLE 3.6

WIND CONVERTER

Performance

1. Design Wind Speed
   - A. Efficiency Goal
   - B. Power Output Criteria
2. Generate Power from Wind Speed 8 mph to 45 mph
   - A. Off Design Power Requirements
3. Shut Down Criteria
   - A. Vibration Detection
   - B. Icing
   - C. Structural Failure
   - D. High Wind
   - E. Over Voltage

TABLE 3.7

TOWER

Peformance

1. Method of Installation
   - A. Piling
     - (1) Poured concrete, (2) wood, (3) steel, (4) thermal
2. Free Standing Tower
   - A. Cost Analysis
3. Guy Wires
   - A. Self Tightening or Pre-loaded Guy Wires
4. Stiffness Requirement
   - A. Vibration Analysis of Tower and Installed System
     - (1) Forced and self induced vibration

Power output criteria needs to be compatible with the output of the central power station at the remote site. When specifying wind speed range for generation of power the low side is determined by the mechanical characteristics of the turbine, rotor combination in the neighborhood of 8 mph. On the high side considerable flexibility exists; however, looking at the Barter Island Wind Frequency Distribution in Figure 3.10, 45 mph is out near the high end of the wind frequency distribution but is low enough to be easily achieved by most existing or planned wind turbine converters. Specifying a high side velocity in excess of 50 mph could escalate costs of some of the otherwise competitive systems.

Power output of the wind converter should increase generally as the cube of the wind velocity less some system losses. A specification requiring increasing power output with wind velocity throughout the operating range is consistent with the operating characteristics of most wind turbines (see Table 2.11) and is desirable in order to be able to collect and store energy during high wind periods.

The wind turbine should shut down when encountering any operating condition that would cause it to destroy itself or the system. A vibration detector sensing excessive vibration due to icing on the blades, structural failure, or high wind conditions should be specified to limit or stop blade rotation. Some provision for stopping the rotor or disconnecting the electric circuit such as a voltage regulator is needed to protect the system from over voltage.

3.2.8.2.2 Tower

A tower design check list is shown in Table 3.7. The contractor should be required to perform a load analysis of the tower with wind converter attached and a core sample test of the subsoil to determine the most cost effective way to install the tower foundation and insure sufficient stiffness to prevent self destruction of the tower by forced or self induced vibration.

In the event it is desirable to avoid the maintenance and extra piling required for guy wire installation a self supporting tower can be specified at extra cost. Depending on the conditions of the subsoil the contractor may elect to use either wood, steel, or a special refrigerated thermal pile. Poured concrete piling is not normally used in the Barter Island area because of cost and subsoil conditions.

3.2.8.2.3 Energy storage subsystem

Table 3.8 summarizes the checklist items considered to be important for the energy storage subsystem. Many of the items have been previously discussed in detail and those details have been omitted here; however, items not previously discussed are covered below.

The nominal charge and discharge power are defined as a result of the system specification, but any unusual overloads such as the 20 kilowatts for 12 hours for a nominal 10 kilowatt system or peak loads such as, for example, 100 kilowatts for 1 second must be specified. The energy efficiency range of 80-85% is difficult to measure during operation or change for a particular battery but is provided as a guide for reference. The reference to non-sparking and electrical insulation relate primarily to maintenance and tool requirements because of the presence of explosive vapors or the possibility of accidentally short circuiting the battery during maintenance operations.

3.2.8.2.4 Power conditioning and control

Table 3.9 is a listing of the power conditioning parameters that require consideration during the specification and design of a wind power system. Since most of the items have previously been discussed, further discussion of them would be redundant. The overload capability is of interest because there are three inverters operating at

TABLE 3.8

STORAGE SYSTEM

I. Performance

1. Energy Content

   A. Total = $\frac{4}{3}$ (Load) x (Disch. Time) x $\frac{1}{\text{(Inverter Eff.)}}$

   B. Module (Max) = $\frac{1}{4}$ Total

2. Power - Charge and Discharge

   A. Nominal Depends on Operating Point Selected

   B. Overload to Be Specified

   C. Peak to Be Specified

3. Voltage

   A. Charge 100-115 Max (Upper Limit Tightly Regulated)

   B. Discharge 100-85

4. Efficiency (Energy) 80-85%

5. Charge Characteristics

   A. Charge Time

   B. Modified Constant Potential

II. Materials and Construction

1. Compatible with Sulfuric Acid Splash and Vapor
2. Non-sparking
3. Electrically Insulated

III. Level of Component Replacement

1. Cell Block
2. Scanner

IV. Redundance

1. Multiple Strings
2. String Isolation

V. Diagnostic Capability

1. Cell Monitoring and Comparison
2. Degradation Monitoring
3. Impending Failure Warning
4. Fault Detection and Identification

TABLE 3.9

POWER CONDITIONING AND SYSTEM CONTROL

Performance

1. Power (Input/Output)
   - A. Nominal to be Specified
   - B. Overload (1.5) x Nominal
   - C. Peak (1.95) x Nominal
2. Voltage
   - A. Maximum 115
   - B. Nominal 100
   - C. Minimum 85
3. Efficiency
   - A. Function of Load and Power Factor
   - B. Function of Temperature of Environment
   - C. Function of Input (85-115 VDC)
   - D. Goal 80-90% Overload Range 60-100% Full Load
4. Controls for Output
   - A. Load
   - B. Power Grid
5. Controls for Charging Storage System
   - A. Wind Turbine
   - B. Power Grid
6. Controls to Insure Degraded Mode Operation of the System
   - A. Modularity
   - B. Parallel Operation
7. System Transient Response and Recovery
   - A. Power Surge
   - B. Lightning
8. EMI

2/3 rated load and each could be loaded an additional 1/3 rated load or 50 percent. The peak capability is due to the ability of many inverters to carry a short duration overload of about 130 percent of their rated load. It also must be recognized that the control functions change depending on whether the system supplies a load directly or operates into a power grid.

3.3 PHASE II CONCLUSIONS AND RECOMMENDATIONS

The research in this phase of the program has shown a highly reliable, cost competitive, wind power system is practical for development and installation at remote sites. The analyses showed that a power system rated at a total power of 10 kilowatts requires four or five nominally rated 8 kilowatt wind turbines at Bar Main, Barter Island, Alaska due to the low wind speeds encountered at this location. Reduction of the total power to 5 KW with two 8 KW wind turbines is also a logical option. In the event the power is reduced, subsystems such as energy storage should be reduced in size. The development of a family of large size sealed lead acid battery cells in the capacity range of 100 to 1000 ampere hours is recommended because of their desirable performance, maintenance, and safety features coupled with their demonstrated low cost in small size units.

Since the proposed wind energy system is a new design it should be fully instrumented and accurate records maintained on down time, power generated, failures, replacements, and maintenance operations. After presentation of the results of the program to the sponsoring organizations, four specific tasks were recommended for future effort and are listed below.

1. Five Kilowatt Configuration Study - Using the existing analysis methods developed for the 10 KW case, reexamine the design issues for a nominal 5 KW, 120 KW-hr storage requirement, using the same modular design philosphy and power form requirements assumed for the 10 KW case. The major objective is to evaluate the configurational similarity between the two design points.

2. Stand By Power/Storage Capacity Optimization - The purpose of this task is to identify the most attractive integrated wind energy/ diesel backup power system configuration. Design considerations shall include electrical interfaces, load transfer, and battery vs. diesel utilization strategies during periods when available wind power is inadequate to meet an assumed constant baseload capacity design criteria for this class of high reliability, combined wind/storage-diesel back up power systems. Consideration should also be given to load peaking capabilities attainable through simultaneous use of both the wind and diesel systems.

3. Dynamic Simulation of Variable Input/Output Power Systems - The objective of this task is to develop a general quasi-steady design methodology for sizing power systems which employ fluxuating energy inputs (e.g. wind/solar) and service variable loads. The dynamic behavior of the entire system (converter, storage, power conditioning, and control functions) is of interest for small self-contained power systems.

4. Small Scale Hybrid Systems - The use of wind and insolation in a hybrid energy system has been suggested[38] and candidate remote Naval Facility locations have been analyzed. Reference 38 recommends Tudor Hill Laboratory on Bermuda as the site for testing a hybrid system composed of a 60 KW (peak) array of solar cells, several 12 KW Swiss Elektro wind plants, a back up diesel generator, and possibly some battery storage units. Extended analysis of remote locations within continental United States is needed to determine negative correlation characteristics of wind and insolation energy and thus the potential advantage to be derived from hybrid systems in these locations. Since power requirements at inland remote sites are not large a small scale prototype composed of a 2-3 KW wind converter, a 1-2 KW (peak) array of solar cells, battery storage, system control, power conditioning, and diesel or power grid backup could contribute significantly to solving system problems and compiling a data base for operation of hybrid systems. Lessons learned on the small scale

prototype could be applied in building and operating larger systems tailored to requirements at specific remote site locations. This concept becomes increasingly attractive as solar cell arrays come down in cost.

SECTION 4

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APPENDIX A
PHASE I - LITERATURE SEARCH

A.1 ABSTRACT OF LITERATURE ARTICLES

During the course of the Literature Survey, hundreds of abstracts of technical papers and articles were reviewed. Areas of interest were wind machines and systems, energy storage and inverters; over one hundred pertinent papers were obtained. These reports were examined and the most pertinent ones are summarized and listed in this report under the same categories.

A.1.1 Wind Machines and Systems

A General Electric Company report entitled "Wind Energy Mission Analysis" surveys the development of wind energy systems in the U.S. Wind potential, electric utility applications, residential, agricultural and remote community applications are discussed and analyzed.[1]

The major principles affecting the proper match between rotor and generator characteristics to achieve optimum performance are described by Goodrich.[2] These are shown important considerations in designing wind power systems.

The utilization of wind power in Denmark with the designs of various Danish wind power plants are discussed by Stein.[3] Price lists for the plants and prices for direct current generators for the wind power plants are shown and compared.

The design of horizontal axis, low solidity, high performance wind turbines is related in a paper by Miller.[4] A refined momentum theory for wind turbine analysis, performance tradeoffs between constant RPM and constant velocity operation, aerodynamic vortex theories for blade loadings and a wind tunnel experimental investigation of a scale model wind turbine are among the topics in the paper.

Grover and Veneruso[5] and Banas[6] describe the Sandia Laboratories Vertical-Axis Wind Turbine project. The status of the general design efforts in the areas of aerodynamics, structures, and testing are discussed.

The aerodynamic, mechanical, operational and manufacturing considerations for a Darrieus rotor vertical axis wind energy converter are developed by Bankwitz.[7] Design techniques and studies are described. In another paper Strickland[8] shows a multiple streamtube performance prediction model for the Darrieus turbine. The model predicts the performance of small scale-rotors more accurately than the single streamtube model and is capable of predicting the overall rotor power output and the distribution of the aerodynamic forces along the rotor blades.

Optimization and Characteristics of a Tailwind Windmill Rotor are developed in a paper by Maughmer.[9] He includes a detailed accounting of the development and operational technique of the Princeton moving-vehicle windmill testing facility. The results and conclusions of an extensive wind-tunnel test program, aimed at a quantitative determination of the aerodynamic penalties associated with numerous simplifications of the basic double membraned cross-section, are discussed.

A wind turbine patent application including a drive motor with elongated blades each having a central outwardly curved portion of airfoil shape is discussed by Blackwell.[10] The wind turbine rotates at a tip velocity to wind velocity ratio greater than about 3 or 4.

"The Engineering of Wind Systems" by Banes[11] discusses the engineering of wind systems from the point of view of component selection and performance assessment. Combinations of variable and constant speed rotors with various turbine types connected by fixed-gear-ratio transmissions are among the systems investigated. The engineering problems are discussed qualitatively, emphasizing the nature, magnitude, and variability of the problems. In the same vein, Eldridge[12] provides a brief survey of the present status and future potential of various types and sizes of wind machines that might be used to meet future energy demands of the U. S. Also discussed are various applications of wind machines, as well as siting problems, performance characteristics and system designs for such machines.

Smetana[13] states that under some circumstances, vertical axis wind energy machines will be superior to horizontal axis machines on a power output/cost basis. He suggests vertical axis systems are desirable in that they are easy to use in a modular fashion and will meet a variety of wind and load conditions.

Walters[14] describes theoretical and experimental research concerning two concepts for wind machines. The first concept is that of a vortex concentrator and the second is that of a vertical axis device with circulation controlled airfoils for blades. Another innovative concept by Western Gear Corporation[15] makes use of augmented flow to drive a wind motor.

The electrical outputs of variable speed constant frequency (VSCF) and constant-speed, constant frequency (CSCF) electrical generation schemes for wind power plants are analyzed on the basis of power-duration curves by Smith and Devaiah.[16] Calculations show the VSCF systems have a slightly higher energy output than CSCF systems.

A wind wheel for electric power generation is projected by Kloss[17] in his paper. The interaction between the wind wheel and generator is accomplished with a power control device to prevent over-loading the generator when the wind velocity increases. The angle of attack of the turbine blade is adjusted to compensate for wind velocity.

A technique for designing wind generation plants to produce electrical energy at a minimum cost is proposed by Johnson.[18] Several design variations are analyzed and a design that minimizes the cost of the produced energy is developed.

The standardized UVEU-(1-4)-6 wind electric power unit is discussed be Fedotov and Kharitonov.[19] The unit is suitable for operation at small sites which are distant from power networks and do not have a high power demand. Output and engineering characteristics of the unit are given.

A number of novel approaches which can be employed to utilize wind energy are described by Black.[20] He suggests the use of a diffuser shroud makes it possible to double efficiency. Vortex augmentation is also discussed as a means of increasing the power output of wind power generators. Commercially available designs are compared. The report states that vertical axis generators have the advantage that the rotor blades can accept the wind from any point on the compass.

The Energy Research Administration published a German translation of an analysis of structural components which are important for wind energy systems.[21] Advantages and disadvantages, such as the type of construction, novelty, susceptibility to failure, ease of repairs, and maintenance are treated. Expected power, performance, and manufacturing and economy are developed and analyzed.

Jayadev[22] discusses a variable speed prime mover which would drive a conventional AC generator with DC excitation, resulting in variable frequency. Constant voltage would be obtained by means of voltage regulator techniques. Converting the output of wind energy systems to utility grade power by means of cost effective techniques is also discussed.

A wind powered generator in which a rotor is encased in a shroud is given by Tramini.[23] The novel design and operating characteristics are developed and analyzed.

A formula for designing the optimal configuration of rotor blades for horizontal wind energy converters is proposed by Weber.[24] The formula predicts the total efficiency of a wind energy converter blade array and on that basis constructs a formula relating rotor blade configuration and efficiency with the aid of some auxillary geometrical functions.

The optimal design criteria of wind powered generators in relation to parameter groups is described by Hutter.[25] They are as follows:

1. the rotor blade parameters,
2. the correlation of the rated power output, the magnitude of the disc area swept by the rotor, and wind velocity statistics,
3. the parameters of the energy conversion.

Brown and Warne[26] conducted a study of the feasibility of generating electric power from wind generators at remote sites in Northwestern Ontario. Of special interest in their paper was the summary of a survey of commercially available wind driven electric plants, the matching of available plant to wind regimes to predict annual energy production, and a systems analysis of pure diesel, hybrid wind/diesel and pure wind electric plants to determine the cost of power from the various alternatives.

The interface dynamics between the rotor and electrical generator for horizontal-axis constant RPM wind turbine systems is analyzed by Mirandy.[27] He concluded that vibration isolation can be accomplished via a *soft* drive shaft.

Parker and Walton[28] presented the results of an annual survey of private firms engaged in the manufacturing and distribution of wind energy conversion systems in the U.S. between 1975 and 1976. Imports are also considered.

A system utilizing axisymmetrical shrouds for windmills that are augmented by ring shaped flaps is described by Seginer.[29] The performance is studied experimentally. It was shown that a flap augmented shroud increases the output of an unshrouded turbine of the same diameter by a factor of four.

Hug and Lath[30] describe the aerodynamic performance of a vortex kinetic energy concentrator. The concentrator, a vertical wing, is oriented to the wind direction. The theoretical aspects of concentrating kinetic energy in the trailing wing tip vortex behind a high lift wing is also discussed.

A. 1. 2 Storage Systems

An extensive study[1] of the use of energy storage in conjunction with photovoltaic and wind energy conversion systems was conducted by the Advanced Energy Programs - General Electric Company, Space Division. The report resulting from the investigation of eleven storage methods summarizes and presents the results, conclusions, and recommendations pertaining to the use of energy storage with wind energy conversion systems. The storage methods discussed include mechanical, thermal, electrical and electrochemical types of storage devices. Cost goals of the present to the year 2000 for energy storage vs. storage capacity under different conditions are determined relative to:

1. Application
2. Available wind energy per location
3. Wind system penetration
4. Storage efficiency
5. Fuel price escalation rate
6. Other cost/viability factors.

The Electric Power Research Institute (E. P. R. I.)[2] initiated cost and design studies of state-of-the-art lead-acid batteries for utility application to determine the viability of today's lead-acid batteries for load leveling application. State-of-the-art technology was used to develop battery designs capable of meeting the technical requirements of load leveling. The cost of manufacturing and the ultimite price for the batteries were determined assuming high volume production.

ESB Incorporated[3] has conducted an investigation into the design and cost of state-of-the-art tubular positive lead-acid battery technology to estimate the selling prices for load leveling batteries. Accessories for the batteries judged vital to meeting the E. P. R. I. performance and life requirements are described and priced. These prices include transportation, installation and reuse credits.

Westinghouse Electric[4] has conducted a study of lead-acid batteries for peaking power applications. It was noted that the current production of lead-acid batteries for peaking application is done on a job shop basis. The potential economics of high volume production has not been realized. A cell design was specified and a typical plant size was selected so that an indepth cost analysis could be made of a manufacturing facility dedicated to the production of peaking batteries. An advanced battery design based on technology developed by the Westinghouse Research Laboratories was also analyzed.

Werth[5] describes the ESB Sodium Chloride Cell in his publication entitled, "Sodium Chloride Battery Development Program for Load Leveling." The ESB Sodium Chloride Cell consists of a molten sodium negative, a beta alumince solid electrolyte also serving as a separator, and a positive mix containing both molten sodium chloroaluminate and a farodoic additive. Their goal is to develop a battery with a manufacturing cost less than 1/3 that of industrial lead-acid batteries and a service cycle life of at least 10 years. Cycles 2500 to 5000 deep are expected from the battery. The overall battery module proposed for load leveling is expected to have a specific energy of at least 45 watt hrs/lb and possibly more.

Bush[6] describes General Electric's sodium-sulfur battery development for bulk power storage. His report describes the results obtained in one year of a program that has a long range objective development of a practical electrical energy load leveling system based on the sodium-sulfur battery. His effort focused on the development of a prototype 4 watt cell that possesses the electrical characteristics required for the load leveling mission.

The "water battery",[7] a reversible water electrolyser device which is being developed in a long term research effort at Battelle's Columbus Laboratories was evaluated in an analytical and conceptual design study as a load leveling system. The battery would produce hydrogen and oxygen by the electrolysis of water during periods of off peak electrical demand. During periods of peak demand the water battery would operate in the reverse mode functioning as a fuel cell by producing electrical power through the recombination of the oxygen and hydrogen. The objectives of their study are to develop a conceptual water battery design and to determine the technical and economic impact of the water battery concept.

Batteries[8] can be operated in heat engine cycles analogous to the cycle of usual mechanical heat engines but without the mechanical motion of pistons, turbines, etc. The electrochemical cycles can be used for direct generation of electric power and for storage. The Los Alamos Scientific Laboratory is in the initial stages of development of such engines which can accept heat in the temperature range of 1700 - 900 K then drop the range to 800 - 600 K while doing useful electrochemical work. When used for energy storage, the heat engine cells can be very similar in chemistry and design to various molten salt energy storage cells. Such cells are being proposed for load leveling and vehicle propulsion.

Brown and Monito[9] discuss in detail the basics of the lead-acid battery, including material and fabrication costs for peaking power battery systems in their paper entitled, "Case for Lead-Acid Storage Battery Peaking Systems."

Huges[10] discusses the theoretical and experimental studies on high pressure electroanalysis producing hydrogen and oxygen for energy storage and reconversion. High pressure hydrogen and oxygen fuel cells with nickel electrodes are investigated for the effects of temperature, pressure, and membrane porosity.

Allison[11] describes a means of energy storage for a wind or solar system that utilizes electrolysis cells to disassociate water into its component gases then stores the hydrogen as a high pressure gas, as a liquid or as a hybrid. The system being developed at Oklahoma State University is described, giving performance parameters for the components of the system that have reached the prototype stage, giving the basic performance and economic parameters that must be satisfied before such a system becomes practical.

Huges and his associates[12] present an overview of Oklahoma State's work in energy storage. Special attention is given to high pressure fuel cells, high pressure electrolysis systems, and the aphodid burner turbine generator.

Hadley[13] describes research and development program aimed at improving the weight, life, and performance characteristics of hydrogen-oxygen alkaline fuel cells for advanced power systems. It discusses the steps taken to improve the life and economic factors of the battery.

Levine[14] discusses the development and status of the sodium sulfur secondary cell which uses fine hollow glass fibers as the electrolyte. Laboratory cells have been built and run at various cycle depths up to 95% of capacity. It was determined that lifetime is not affected at depths of discharge to at least 50% or more. The types of failure modes observed were progressive weakening and breaking of the fibers inside the cell assembly and fiber breakage at the fiber tube interface.

Klein and Baker[15] describe the nickel hydrogen secondary battery system. The system possesses the advantages of long cycle life, insensitivity to overcharge and reversal, and high energy density. The system constraints are reviewed when utilizing the self contained cells as a building block. Heat generation and transfer, charge and overcharge control, multicell grouping and individual cell bypass are discussed. It is estimated that a 28, 50-Ahr battery can run at 80% depth will deliver 18 Whr/lb and near term improvements will raise this to 20 Whr/lb.

Miller[16] discusses a low cost nickel hydrogen battery design concept. Considerable cost reduction is achieved through the utilization of the multiple cell per single battery pressure vessel concept, standardization of components and design versatility with an ability to meet varied user requirements with only minor modifications.

Argonne National Laboratories[17] are in the process of conducting tests on High Performance Batteries for stationary energy storage and electric vehicle propulsion. The report obtained describes their efforts and the results of their proceedings and the problems encountered.

Douglas[18] discusses the concept of using secondary batteries for bulk storage of electric energy. Todays advanced technology is discussed and advanced battery development is reviewed. Existing and future battery systems are presented and their advantages and performance outlined.

Eldridge[19] discusses different energy storage options. The systems discussed fall into the categories of electrochemical energy storage (batteries or stored hydrogen generated by electrolysis), thermal energy systems, kinetic energy systems (flywheels or electromagnetic systems) and potential energy systems (pumped hydro and compressed air systems).

A.1.3 Inverters

Some information regarding inverters systems was found. One system,[1] described in "Wind Conversion Systems: Workshop Proceeding Publication Prepared by Lewis Research Center", discusses a wind powered synchronous AC/DC/AC converter system. Two such systems[2] being modelled at the University of Wisconsin. On interest in the above systems is that the systems use silicon-control-rectifier inverters. During off peak periods the SCR Inverter can operate in rectifier mode to charge batteries.

A survey of manufacturers and distributers had promising results. There are commercially available inverter systems that can rather easily be modified to meet the specified needs. These systems are specifically designed to work with a utility network. The principle behind these inverters is that when excess electricity is being generated, the inverter can put the electricity into a waveform compatible to that of the utilities and feed it back into the utility network, which acts as an infinite storage system. This type of system can be modified to rectify the DC from a battery storage system into suitable AC power.

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APPENDIX B

COMPUTER PROGRAM FOR SYSTEM ANALYSIS

This program calculates and plots electrical power output as a function of battery recharge time, battery energy efficiency, and inverter efficiency for a wind energy system.

```
      C
            REAL POWER(34),CTIME(34),PWMILL,NINV,NBATT,DTIME
            PWMILL=5.3
            DO 7 J=6,24,6
            DTIME=1.*J
            DO 8 K=70,90,5
            K1=K
            NBATT=K/100.
            DO 9 L=60,95,5
            L1=L
            NINV=L/100.
            DO 6 I=1,34
            POWER(I)=CTIME(I)=0.
      6     CONTINUE
            DO 10 M=1,34
            CTIME(M)=3*M-2.
            POWER(M)=PWMILL*NINV*(1./(1.+DTIME/(NBATT*CTIME(M))))
      10    CONTINUE
            PRINT 20
      20    FORMAT('1','LOAD POWER (KW) AS FUNCTION OF CHARGE TIME')
            PRINT 30,DTIME,K1,L1,PWMILL
      30    FORMAT('+',60X,'DTIME=',F3.0,5X,'NBATT=',I3,5X,'NINV=',I3,5X,'PWMI
           *LL=',F6.2)
            PRINT 40
      40    FORMAT('0',57X,'POWER IN KILOWATTS')
            CALL PLOT 2 (CTIME(1),3.,34,POWER,POWER)
      9     CONTINUE
      8     CONTINUE
      7     CONTINUE
            STOP
            END

      $ENTRY
            SUBROUTINE PLOT2(X,DX,N,Y,YC)
      C PLOTS TWO FUNCTIONS, USE ON BATCH, WATFIV ONLY
            REAL BLANK/' '/,DOT/'.'/,A/'X'/,XI/'I'/,DASH/'-'/
            REAL PLUS/'+'/,ZERO/'O'/
            REAL LINE (101),SCALE(11),Y(N),YC(N)
            IF(N.GT.1)GO TO 1
            WRITE(6,2)
      2     FORMAT('O N=1, NO PLOT CAN BE MADE',/)
            RETURN
      1     XT=X
            TMAX=AMAX1(Y(1),YC(1))
            TMIN=AMIN1(Y(1),YC(1))
            DO 200 I=2,N
            IF(Y(I).LE.TMAX.AND.YC(I).LE.TMAX)GO TO 201
            TMAX=AMAX1(Y(I),YC(I))
            [illegible] Y(I).[illegible].TMIN) GO TO 201
```

```
          TMIN=AMIN1(Y(I),YC(I))
   200    CONTINUE
          IF(TMAX.NE.TMIN) GO TO 13
          IF(TMAX.NE.0)TMIN=-TMAX
          IF(TMAX.EQ.0) TMAX=1
    13    DO 3 I=1,11
 3        SCALE(I)=(I-1)*(TMAX-TMIN)/10.+TMIN
          WRITE(6,110)SCALE
 110      FORMAT('0',3X,11F10.4)
          DO 101 J=1,101
  101     LINE(J)=DOT
          DO 105 J=1,101,5
  105     LINE(J)=XI
          IO=-TMIN/(TMAX-TMIN)*100.+1.
          IF(IO.LT.0.OR.IO.GT.101) GO TO 120
          LINE(IO)=ZERO
 120      WRITE(6,102)LINE
 102      FORMAT('0',10X,101A1)
          DO 103 J=1,101
  103     LINE(J)=BLANK
          DO 210 I=1,N
          LINE(1)=DOT
          J=(Y(I)-TMIN)/(TMAX-TMIN)*100.+1.
          LINE(J)=A
          JK=(YC(I)-TMIN)/(TMAX-TMIN)*100.+1.
          IF(((I-1)/10*10).EQ.(I-1).OR.I.EQ.N) GO TO 107
          WRITE(6,104)LINE
 104      FORMAT(' ',10X,101A1)
          LINE(JK)=PLUS
          WRITE(6,115)LINE
    115   FORMAT('+',10X,101A1)
          GO TO 109
  107     LINE(1)=DASH
          WRITE(6,108)X,LINE
 108      FORMAT(' ',F7.2,3X,101A1)
          LINE(J)=A
          LINE(JK)=PLUS
          WRITE(6,116)X,LINE
    116   FORMAT('+',F7.2,3X,101A1)
    109   LINE(J)=BLANK
          LINE(JK)=BLANK
          X=X+DX
  210     CONTINUE
          X=XT
          RETURN;END
```

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