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HIGHWAY DEPARTMENT DEMONSTRATION OF SOLAR AND WIND ENERGY

by

H. Roland Zapp
Jes Asmussen
Gary Anderson

Division of Engineering Research

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COLLEGE OF ENGINEERING

MICHIGAN STATE UNIVERSITY

EAST LANSING, MICHIGAN 48824

Abstract

The detailed solar system design for the highway information and rest station in Niles, Michigan has been completed. The design includes active energy conversion from photovoltaic and wind systems and passive conversion from a Trombe wall and earth sheltered structure. Photovoltaic and wind component specifications were prepared and the response from industry evaluated. Based on the accepted manufacturer's bids, life cycle costs were prepared for each solar energy component. In addition the performance and life cycle cost for the Trombe wall was completed. The thermal conduction losses from the earth sheltered facility were also evaluated. Sensors for on-site data monitoring were identified and a data recording system was designed and evaluated. Assistance was provided in obtaining federal support for the solar addition to the rest station.

EXECUTIVE SUMMARY

This document emphasizes the findings of the phase III effort (of a four phase effort) which spans the period January 1, 1979 to July 15, 1979. The anticipated phase IV effort is expected to be a low level effort to begin after system installation. The tasks completed during phase III are as follows:

A. Solar Photovoltaic

1. Provided specifications for and identification of manufacturers of solar cell panels.
2. Provided specifications for and identification of manufacturers of power and environmental sensors.
3. Evaluated proposals from manufacturers in response to letters requesting proposals.
4. Assisted in obtaining federal support and in providing information required for that federal support.
5. Developed the life cycle cost analysis for the photovoltaic system.
6. Assisted in developing the total system layout. Attended meetings with Indiana and Michigan Electric Company, Department of Transportation representatives, and component suppliers to evaluate the system design.
7. Identified potential interface problems between the solar electric - wind systems outputs and the public utility supply.

B. Wind Electric

1. Completed review of proposals submitted by manufacturers and in cooperation with MDOT chose final Wind Turbine Generator (WTG) design.
2. Using the chosen WTG and photovoltaic systems, the electrical system design--including start-up and shutdown of units, high wind protection, utility line safety, etc.--was completed. The interaction problem between the two WTG and the photovoltaic systems was reviewed.

3. Reviewed WTG construction and installation problems, space requirements, requirements for batteries, location of towers and space required for each, public safety requirements and vandalism possibilities.

4. Identified potential electric utility system interface problems. The potential problem areas considered include:
   a. Safety for utility linemen and Niles information center personnel.
   b. Rf noise and harmonic content of solar/electric generated waveforms with the objective of suppressing the harmonics.
   c. The need for power factor correction for individual WTG and for the entire solar system.
   d. Acoustic noise.
   e. Lightning protection.
   f. Interaction between inverters.

5. Completed the life cycle analysis for each WTG (using actual WTG characteristics and utility rate structures).

6. Reviewed proposed WTG measurements to assure that measurement information is both sufficient and gathered according to MDOT contract standards.

C. Miscellaneous Solar Efforts

1. Sensor and Data Acquisition components and design
   a. Identified environmental and power distribution sensors and potential suppliers for total system monitoring and public display. Located sensors in the overall system layout.
   b. Assisted in identifying the specific computer system to monitor energy generation, electric power distribution and environmental conditions to permit total system performance evaluation.
   c. Developed initial software to verify computer operation and system shakedown.

2. Assisted in design and analysis of a Trombe wall; including analysis of performance, life cycle cost analysis, identification of manufacturers of motorized thermal curtains and of phase change material suppliers.

3. Provided calculations on the thermal performance of a ground sheltered facility.

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Introduction

Michigan State University was contracted by the Michigan Department of Transportation (MDOT), in the summer of 1978, to design, analyze, and evaluate the feasibility of a solar and wind electric addition to a new Highway rest and information station south of Niles, Michigan. In response to decreasing availability of fossile fuels, at a time when energy consumption is growing rapidly, the Michigan Legislature introduced bills which require the addition of solar systems to new highway rest stations. Therefore, to provide the Highway Department personnel with operational experience with the most likely solar-electric candidates of the near term, a combination wind/photovoltaic system interfaced directly with the utility supply was developed. In addition, to encourage passive energy collection, the facility was designed to be partially constructed underground and to have a south facing Trombe wall.

The objective of this initial, sophisticated, solar system was not to provide low cost energy but rather to serve as a test facility to provide MDOT with operation and performance experience, to provide extensive visibility of alternative energy sources, to make motorists energy conscious and to encourage energy conservation. However, as this project evolved, the economics of the alternative energy sources have begun to look more favorable. The wind system already appears cost effective on a life cycle basis and the decreasing cost of solar photovoltaic cells promises to produce cost effective energy in the near future.

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1.0 Technical Description

The design and evaluation of a hybrid wind-solar electric and passive solar system for the Niles U.S. 31 rest station has been completed. The design is intended to supplement the utility supplied electrical energy, provide extensive public visibility and assist in evaluating solar system performance for highway rest stations. Detailed weather data was utilized in phase I and phase II to evaluate the energy outputs from wind and solar photovoltaic components and extended in phase III to evaluate the performance of the Trombe wall. In addition, evaluation of a ground sheltered design was carried out. The overall system design concept is shown in Figure 1. In this initial design no consideration was given to storage for reasons of economy as well as for space limitations.

The block diagram of Figure 1 demonstrates a very sophisticated solar system layout with 5 generic energy sources. It is intended that this multi-faceted system will be highly instrumented for data collection and evaluation. The facility must therefore be considered a test bed for evaluating competing energy alternatives for consideration in designing or retrofitting other Highway Department facilities. The central data recorder and processor consists of a 16 bit word microprocessor which can be adapted to system control and energy allocation strategies.

The system block diagram shown in Figure 1 consists of a 4.8Kw (peak rated) Solar Power Corporation photovoltaic array, a 40Kw (peak rated) Energy Development Company WTG and a 15Kw (peak rated) Environmental Energies WTG each interfaced with a Gemini inverter directly to the 3 phase 208V utility grid. Isolation transformers are utilized in each component branch to suppress harmonics and to prevent unbalanced loading. In addition, a substantial fraction of

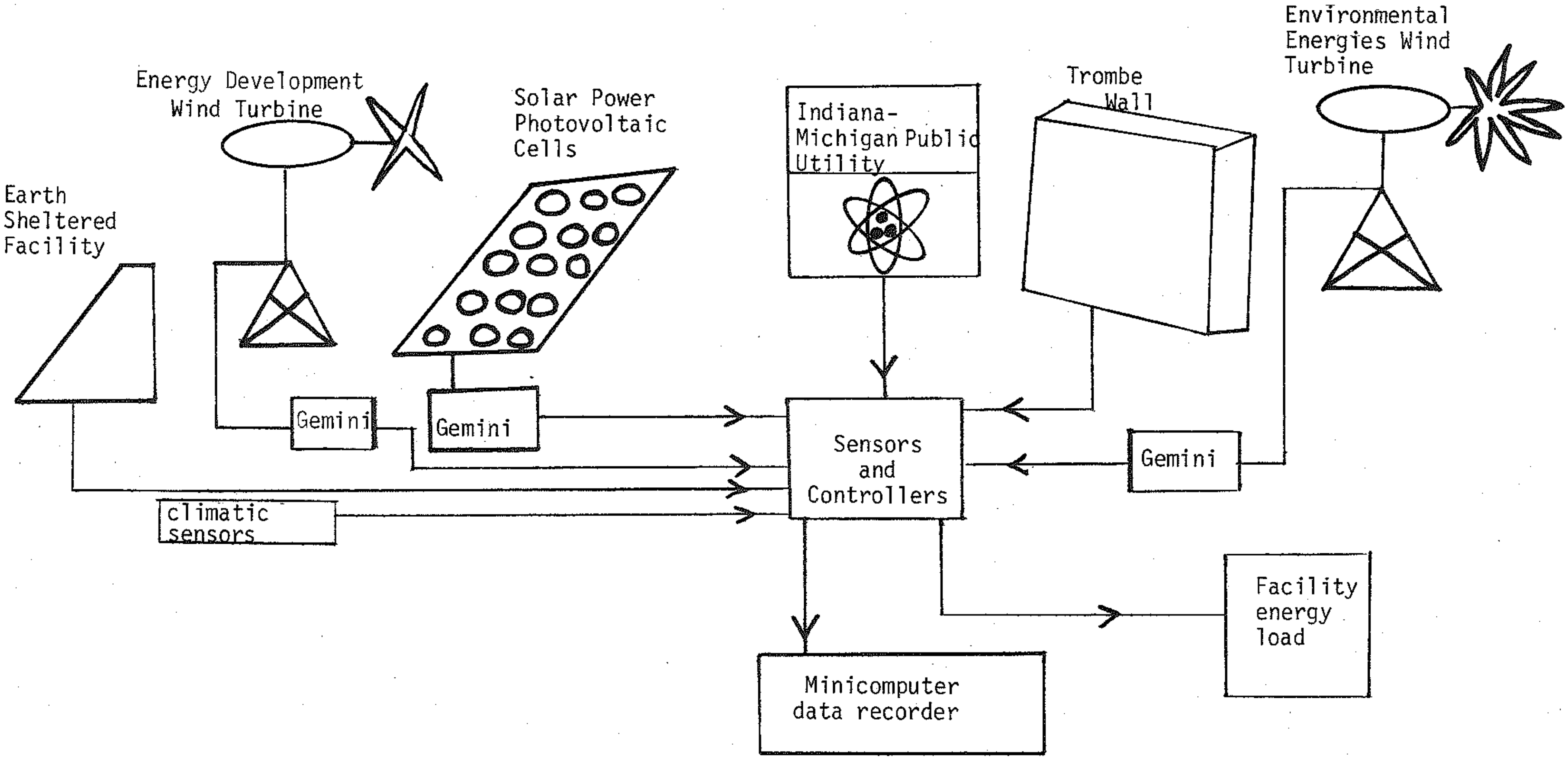


Figure 1. Functional block diagram of hybrid wind/solar electric and passive solar energy system.

the facility is buried underground in order to moderate the heating and cooling loads. A 20% reduction in conduction heat loss from the shell results from the earth sheltered design. A Trombe wall with active air moving controls further assists in reducing the heating load by providing approximately $24x10^6$ BTU of useful heat through 208 ft^2 of dual glazing. The Indiana and Michigan Electric Company provides energy not supplied by the alternative energy sources. A microprocessor collects data from an extensive distribution of environmental and power flow sensors. Each of the above technologies will be discussed in further detail in the following sections.

2.0 Solar Photovoltaic System

In the phase I report the theory of photovoltaic operation and the expected yearly performance based on East Lansing measured climatic data were presented. These findings will not be repeated here. The photovoltaic computer simulation (detailed in the phase I report) output using the East Lansing data was approximately 7,140 Kwhr (without stationary reflectors). This value will be used in calculating the pay back for photovoltaic energy. The stationary reflectors will provide additional energy gain.

As reported in the phase I report, all potential suppliers of photovoltaic arrays were identified. Of these, four of the most promising suppliers were sent requests for proposal based on specifications developed at MSU and contained in the DOT letter attached to appendix A (section A.1). The response from Solarex and Solar Power Corporation were particularly encouraging. Solar Power Corporation cells were chosen for a number of reasons including slightly lower cost, highly acclaimed quality assurance and previous interaction by Highway Department personnel on another project.

The photovoltaic system will be connected to a three phase 208V synchronous inverter (Gemini) to be provided by the solar cell supplier. The photovoltaic system will be instrumented to provide data on:

(1) Solar radiation
(2) Temperature
(3) Current output
(4) Voltage output

A listing of sensors, sensor interfaces, sensor suppliers and expected costs is attached to appendix A (section A.2).

2.1 Solar Photovoltaic Economics

The initial photovoltaics costs and payback were developed and reported in the phase I report. Since that time some costs have been finalized while some of the variables have been modified as required by the federal DOT solar contract. It should be pointed out that the federal requirement place some unfavorable conditions on the MDOT project, in particular the cost of capital is changed from 7% (government tax free bonds) to 10% (commercial cost of money), while the purchased cost of energy from the Cook Nuclear plant is very low (at present the lowest electrical rate in the state of Michigan) and is not considered a fossile fuel for which the federal DOT allows a doubling in the actual cost of the fuel. However, the economics are favorably modified by the lower cost of the photovoltaic system from the estimated $90,000 to the bid cost of approximately $62,000. Even this cost will be reduced in future arrays as designs are simplified, material quantity and costs are reduced and manufacturing processes are automated.

Based on a total solar photovoltaic array cost of $62,000, a component life of 20 years, rate of return on investment of 10% per year, fuel price escalation rate (here considered electrical energy cost escalation) of 10% per year, inflation rate of 7% (not needed since it is assumed the system is maintenance free) and an energy collection without stationary reflectors of 7137 Kwh/year, a number of scenarios are considered as shown below.

For the four cases considered below the following relations are utilized:

$$S_N = (1+r_1)^N IC - \frac{1 - \left(\frac{1+r_1}{1+r_2}\right)^N}{1 - \left(\frac{1+r_1}{1+r_2}\right)} (1+r_2)^N AKWHy_o$$

with $r_1 \neq r_2$; and for $r_1 = r_2$: $S_N = (1+r_1)^N IC - N(1+r_2)^N AKWHy_o$
where

y_o = electrical cost in \$/Kwhr at time N=0

N = pay back period in years

IC = capital investment = \$62,000

r_1 = interest on capital

r_2 = percent per year increase in fuel costs

AKWH = total Kwhr collected each year = 7137 Kwhr

S_N = balance of capital debt after N years.

Case I: The 1979 Kwhr cost based on N=20 year life, $r_1=r_2=10\%$, is $y_o=\$.43$/Kwhr, or approximately ten times the present cost of electrical energy from the electric utility.

Case II: System pay back time based on the conditions of Case I and a present energy cost of $y_o=\$.06$/Kwhr yields a pay back time of N=144 years.

If the cost of capital is reduced to 7% as is the situation for municipal bonds, the pay back time becomes 58 years.

Case III: An additional case of interest is that of the present energy cost in \$/Kwhr for which a 20 year amortization period is postulated with a cost of money to the DOT of 7%. This requires the present cost to be equal to $y_o=\$.32$/Kwhr, a cost still eight times greater than present day energy costs.

Case IV: The final case of interest is that of the required cost of the photovoltaic system to be presently cost effective on a life cycle cost basis. Using interest on capital of 10%, system life of 20 years, fuel escalation of 10% and present fuel cost of $.05/Kwhr, the system must cost no more than $7,137. This is clearly many years into the future.

The above cases are intended to provide only approximate costs for energy from photovoltaic systems. Clearly, for the cheap utility supplied electrical energy available to the DOT rest area, photovoltaic electric energy is not yet competitive. However, the trends suggest that the fossiles and nuclear energy prices are increasing while photovoltaic systems are decreasing in cost. The DOE projections for $.50/watt (in terms of 1975 dollars) by 1986 will result in competitive photovoltaic produced energy.

3.0 Trombe Wall Design and Costs

The tradeoffs between passive energy collection systems versus active energy collection systems are debated at great lengths by energy enthusiasts representing both sides. Clearly, the application of each, along with strict conservation, is necessary in both the near term as well as in the long range. The concern and interest expressed by the MDOT personnel in energy conservation and energy reclamation has opened the door to the application of both passive and active solar energy systems at the new Niles highway rest station. Specifically, the earth sheltered structure and the Trombe wall represent excellent applications of passive design concepts. In this section we will consider the Trombe wall configuration and its economics.

The need for, and cost of, space heating in the Michigan climate represents the largest consumption of energy in residences and structures such as the highway rest station. To reduce their large energy demand, a modified Trombe wall has been designed. The design differs from the conventional passive Trombe wall in that temperature sensors activate air flow. In addition, energy storage is accomplished via a phase change material.

The basic control strategy for the Trbome wall is outlined as follows:

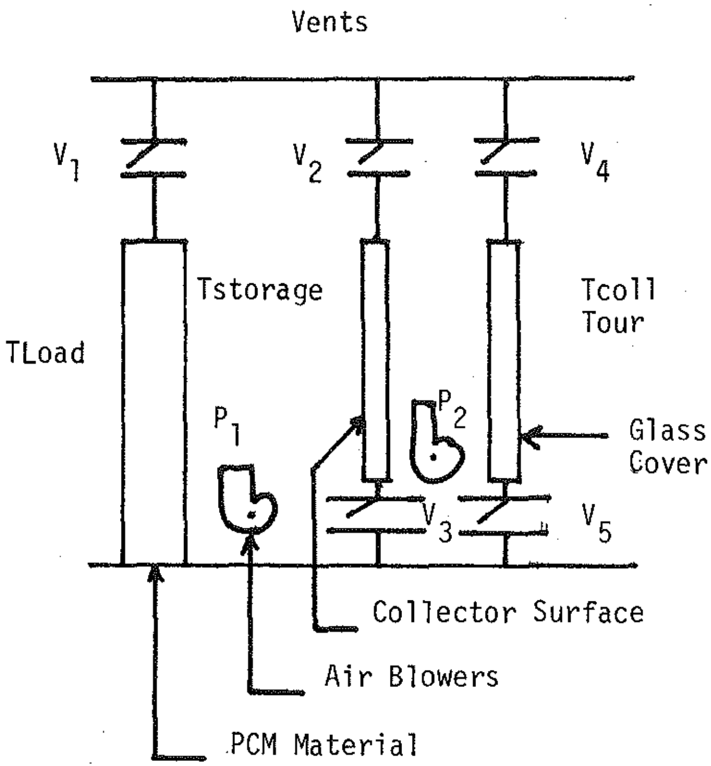
1. Five modes of operation are identified
2. Three control temperature values are defined
3. A basic system concept is postulated

The basic Trombe wall design and variable definitions are shown in Figure 2. The sequence of operation is shown in Figure 3. The fifth mode of operation is that of inactive (no air movement). The controlling temperatures for the operating modes are given as follows:

DIRECT HEATING: (when make-up air is required)	$T_{LOAD} < T_{LO}$ $T_{STOR} < T_{COLL}$
PREHEATING: (when make-up air is required)	$T_{LOAD} < T_{LO}$ $T_{STOR} > T_{COLL}$
SOLAR BYPASS: (when make-up air is required)	$T_{LOAD} > T_{LO}$
EXHAUST: (when no make-up air is required)	$T_{OUT} > T_{HI}$ $T_{COLL} > T_{OUT} + T_{CON1}$
STORAGE: (when no make-up air is required)	$T_{OUT} < T_{LO}$ $T_{COLL} > T_{STOR} + T_{CON2}$
INACTIVE:	All other cases

It should be noted that the solar Trombe wall operation is closely linked to the make-up air system. It is proposed, since the Trombe wall contributes a relatively small amount of energy to the facility, that the heating supplied by the Trombe wall be accomplished only during the time make-up air must be drawn into the facility. This will result in simplified control as well as the efficient use of energy required in meeting make-up air requirements.

The cost of the Trombe wall has been estimated at $8,000. The energy that can be collected by the Trombe wall is based on a number of factors, such as:



Temperature Values

$T_{LO} = 60^o$

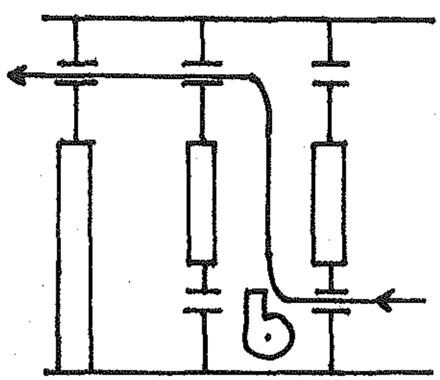
$T_{HI} = 70^o$

$Tcon1 = Tcon2 = 10^o$

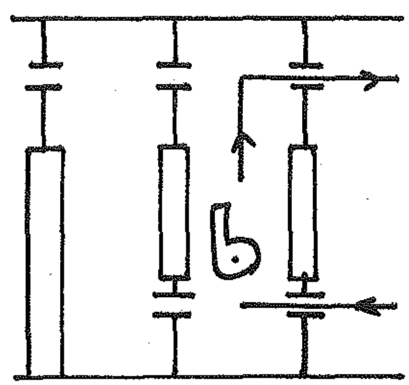
V_i = Vent "i"

P_k = air pump (fan) "k"

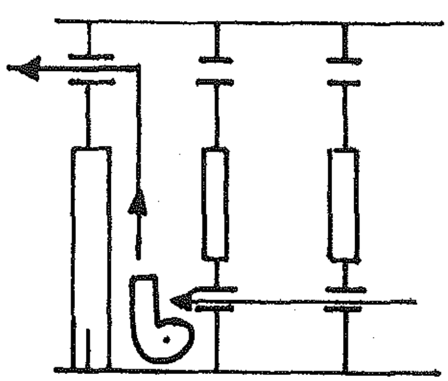
FIGURE 2. TROMBE WALL CONFIGURATION



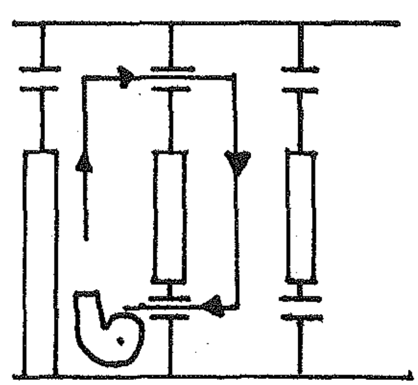
DIRECT HEATING (V_1, V_2, V_5, P_2)



EXHAUST (V_4, V_5, P_2)



PRE HEATING (V_1 V_3 V_5 P_1)



STORAGE (V_2 V_3 P_1)

FIGURE 3. TROMBE WITH OPERATIONAL MODES

(1) Temperatures inside, outside, collector and storage (phase change material);

(2) Make-up air requirements;

(3) Solar radiation incident on collectors;

(4) Collector efficiency as determined by glass reflection, glass absorption, reradiation, conduction and convection losses.

Using Lansing data, along with the program to project this data onto the vertical plane, a reflection coefficient for dual glazing, the control strategy to collect only when the conditions of (1) above are consistent with the previously outlined temperature controls and a collector surface of 9'x26' the collector incident radiation is 76×10^6 BTU/yr. Of this quantity, approximately 58×10^6 BTU/yr or 17×10^3 Kwhr may be collected. The simulation results for the radiation incident on the collector per square meter and the results for that which can be collected based on the temperature controls is shown in table 1.

Table 1. Trombe Wall Simulation Results

DAYS	MONTH	TOTAL RADIATION (KILOWATT HOUR/METER**2)	COLLECTED RADIATION (KILOWATT HOUR/METER**2)
31	January	98,469	98,469
28	February	129,296	129,296
31	March	96,647	96,497
30	April	82,370	61,903
31	May	40,044	24,901
30	June	38,392	3,599
31	July	46,564	.564
31	August	73,427	3,722
30	September	100,494	51,006
31	October	127,938	103,052
30	November	81,563	74,067
31	December	85,185	85,185
	TOTALS FOR YEAR	1000,387	732,261

The pay back economics are summarized in the table below for different interest rates on capital (7%, 10%) and different costs of purchased electrical energy per Kwhr ($.04, $.05, $.06). The entries in the following table are based on a wall cost of $8,000, an energy collection of $17x10^3$ Kwhr, fuel cost increase of 10%, no maintenance and the capital interest and initial fuel costs shown.

initial cost of electricity \ interest on capital	7%	10%
$.04	9.5 yr	11.6 yr
$.05	8.0 yr	9.4 yr
$.06	6.5 yr	7.8 yr

Trombe wall pay back economics

4.0 Earth Sheltered Design Concepts

As previously discussed in the Trombe wall section, the earth sheltered structure concept provides passive solar energy conservation. The reduction in energy requirement is accomplished in the following ways:

(1) Reduction in shell (exterior building surface area) infiltration losses;

(2) Reduction in thermal conduction losses because of the small difference in temperature between the ground and building interior;

(3) Reduction in cooling requirements.

The losses attributed to infiltration losses are typically difficult to evaluate since they depend on type and number of windows and doors, wind conditions, and precise construction techniques. The thermal conduction losses may be calculated based on the ASHRAE standards and techniques. This approach was chosen for the initial facility design where the detailed steps in the calculation are reserved for Appendix C.1. The ASHRAE procedures are based on achieving an interior temperature of 70°F. Since the calculations were made, based on the ASHRAE standards, the federal government has set a new guideline of 65°F for heating and 78°F for cooling for commercial and federal buildings. For purposes of heat loss calculation, to follow the ASHRAE procedure an interior temperature of 60°F is postulated (it is assumed that interior gain from lighting and body heat makes up the additional 5°F). Thus, the new guidelines will further improve the performance of the earth sheltered design since the earth temperature is assumed to be 55°F. A much greater reduction in the degree heating days will occur for underground than for above ground conditions. However, the details on this improvement have not been developed.

As noted above, calculations based on the ASHRAE standards were performed. The results are most dramatic for designs with relatively little insulation. For instance, for an 8" concrete block shell with 1" polystyrene insulation in the ceiling, the conduction heat loss (based on 70°F interior design) is 490×10^6 BTU per year. The same structure with dirt covering the north and west wall as well as some roof area results in a conduction heat loss of only 270×10^6 BTU. For a well insulated structure including 1" polystyrene and 3-1/2 fiberglass batten in all walls and 12" fiberglass in the ceiling, the energy loss is reduced to 130×10^6 BTU which is further reduced to 106×10^6 BTU with earth sheltering. Although the energy saving from an earth sheltered structure are not as impressive for highly insulated structures, a saving of 20% in heating requirements can still be realized. Additional savings from reduction in infiltration loss and from reduced summer cooling will be added to the savings from reduced thermal conduction losses.

5.0 Wind Turbine Generators

The two wind turbine generators (WTG) chosen for this project are manufactured by Energy Development Company and Environmental Energies Inc. These WTG were chosen (1) by first surveying all known WTG manufacturers in the United States and Canada that sell WTG in the size range from 8-50 kW, (2) narrowing down this list to nine manufacturers with the most field test experience and best WTG designs and (3) asking these nine to present proposals according to the project specifications (see Appendix B). A brief summary, together with the calculated month by month energy output of each WTG at the Niles site is given below.

Energy Development Company WTG

Energy Development Company (EDC) of Hamburg, Pennsylvania has developed a series of four bladed, downwind, fixed pitch WTG. These machines are significant in that they offer the most cost effective WTG-generated electricity in the United States today. They are competitive as fuel savers for many REA and small municipal systems where winds are in excess of 10 mph at 30 feet.

The design approach has been to use off-the-shelf technology for gear boxes, generators, towers, etc. whenever possible. The blade construction is simple and can be performed in small workshops with hand tools and low cost labor. The machines are offered without slip rings and use three, four-foot diameter, rolled steel pipes for towers. Each machine has four, fixed blades although an additional two blades can be purchased to improve power output in low wind regions. Two utility interconnect options are available (1) an alternator/direct current/battery/synchronous inverter utility interconnect concept and (2) an inductor generator concept. A third concept that was discussed during this project involves a wound-rotor induction machine where the rotor terminals are connected to electronic circuits that appear resistive to the rotor while converting slip-frequency power to line-frequency power and dumping this rotor power back onto the power grid. The output power from this induction machine comes from both the stator and the rotor. Thus, this electrical machine concept is called a double output induction generator (DOIG).

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*At the time of proofing this report (Spring 1980) EDC is only selling a six-bladed 40 kW induction generator option.

The standard Energy Development machines, operate at low rpm and have been designed for the low 10 mph wind regimes of Pennsylvania. No feathering is required for overspeed control since the machines shut down during winds greater than 40 mph, and they have been designed to withstand wind gusts up to 120 mph. There are at least 10 EDC WTG installed and interconnected with three utilities in the Pennsylvania region. One machine, a 250 kW, 60 foot diameter design, is installed in Dorney Park, an amusement park in Allentown, Pennsylvania. Pennsylvania Power and Light Co., recognizing the potential of these WTG for their customers and possibly other utilities, have purchased a 45 kW machine and installed it on a mountain plateau 1800 feet above sea level, three miles west of Hazleton, Pennsylvania. Trial runs began in October 1978 and still continue.

The calculated month by month energy outputs of the 45kW (battery option) WTG are shown in Table 2. This WTG is 38 feet in diameter and has a cut-in velocity of 7 mph (~3m/s), rated velocity of 27 mph (~12m/s) and cut-out velocity of 40 mph (~18m/s). The calculations used 1974 South Bend, Indiana airport wind records height corrected to 50 feet and 70 feet.

Environmental Energies Allison WTG

The Environmental Energies WTG is a multibladed, downwind, horizontal axis machine which is rated at 15kW at 25 mph. This machine employs four sets of two blades 24 feet in diameter to provide the high efficiency, slow speed airfoil suited for low wind speed sites common to most of Mid Michigan. The drive train and the shunt wound generator are "off the shelf" items and the utility interface is provided by a line commutated synchronous inverter. Table 3 summarizes the month-by-month performance in South Bend airport winds.

5.1 The Durable Output Induction Generator (DOIG) Energy Development Company 45kW WTG

During the period of this investigation it was suggested that the standard EDC 45kW machine be redesigned to operate as a VSCF (see Appendix B.3 for definitions) DOIG, thereby

Table 2

Energy Development Company -
Standard 45 kW WTG (with batteries)

Month	Avg. Wind Speed (mph) (21 ft)	Energy Output (kWh)* (50 ft)	Energy Output (kWh)* (70 ft)
Jan	12.2	8,000	8,700
Feb	12.9	8,900	9,700
Mar	12.4	8,900	9,800
Apr	14.9	11,300	12,200
May	10.5	6,800	7,300
Jun	10.3	6,100	6,800
Jul	8.8	4,500	5,200
Aug	8.4	4,200	4,500
Sep	9.1	4,800	5,400
Oct	10.2	6,300	7,000
Nov	11.1	7,500	8,200
Dec	10.5	6,800	7,733
YR	11.0	85,500	93,800

*(.17 height correction)

Table 3

Environmental Energies Allison WTG

Month	Avg. Wind Speed (mph - 21 ft)	Energy Output (kWh)* (50 ft)	Energy Output (kWh)* (70 ft)
Jan	12.2	3,300	3,700
Feb	12.9	3,500	3,900
Mar	12.4	3,600	4,000
Apr	14.9	4,900	5,500
May	10.5	2,600	2,800
Jun	10.3	2,200	2,500
Jul	8.8	1,500	1,700
Aug	8.4	1,400	1,600
Sep	9.1	1,700	1,900
Oct	10.2	2,300	2,600
Nov	11.1	2,800	3,200
Dec	10.5	2,500	3,000
YR	11.0	32,000	37,000

*(.17 height correction)

increasing the energy output and hopefully improving the WTG economics. The redesign was to involve only changing (1) the 45 kW generator to a wound-rotor, 40 kW double output induction generator (DOIG) and (2) adding the additional inverter and controls to synchronize the rotor electrical energy to the 60 Hz line (see Figure B.3-7). It was estimated that the total WTG system cost (IC) would increase from $36,300 to $45,000 with this design change. The economic calculations presented in the next section show that the increased cost of the DOIG is not compensated by a large enough increase in energy output. In fact, the economics of this DOIG redesign are not as attractive as the standard EDC 45 kW WTG. Based on these preliminary calculations it was decided not to pursue the DOIG redesign.

This analysis does not suggest that a DOIG WTG may not have economic merit if redesigned differently than that proposed above. For example, consider the following example where the characteristics of the Pennsylvania Power and Light Company EDC WTG are used (see the solid lines in Figure 4). These characteristics show almost linear behavior between cut-in and rated wind speeds. The machine is a 45 foot diameter, 45 kW fixed pitch, four bladed WTG that has been tuned to the low average winds of Pennsylvania. Efficiencies shown in parenthese in Figure 4 vary between a maximum of 0.49 at 16 mph to 0.29 at rated wind speed (27 mph). While these efficiencies appear high (especially if they refer to electrical output), they will be used here since they are the only such values available in the open literature.

The equivalent "ideal" VSCF is assumed to have the same aerodynamic system and operate at the tip speed to wind speed ratio required for maximum efficiency from cut-in to rated wind speeds. Thus this ideal VSCF system has an assumed constant efficiency of 0.49 between cut-in and rated wind speeds and a rated power of 75 kW. The machine characteristics of this "ideal" VSCF are shown as dotted lines in Figure 4.

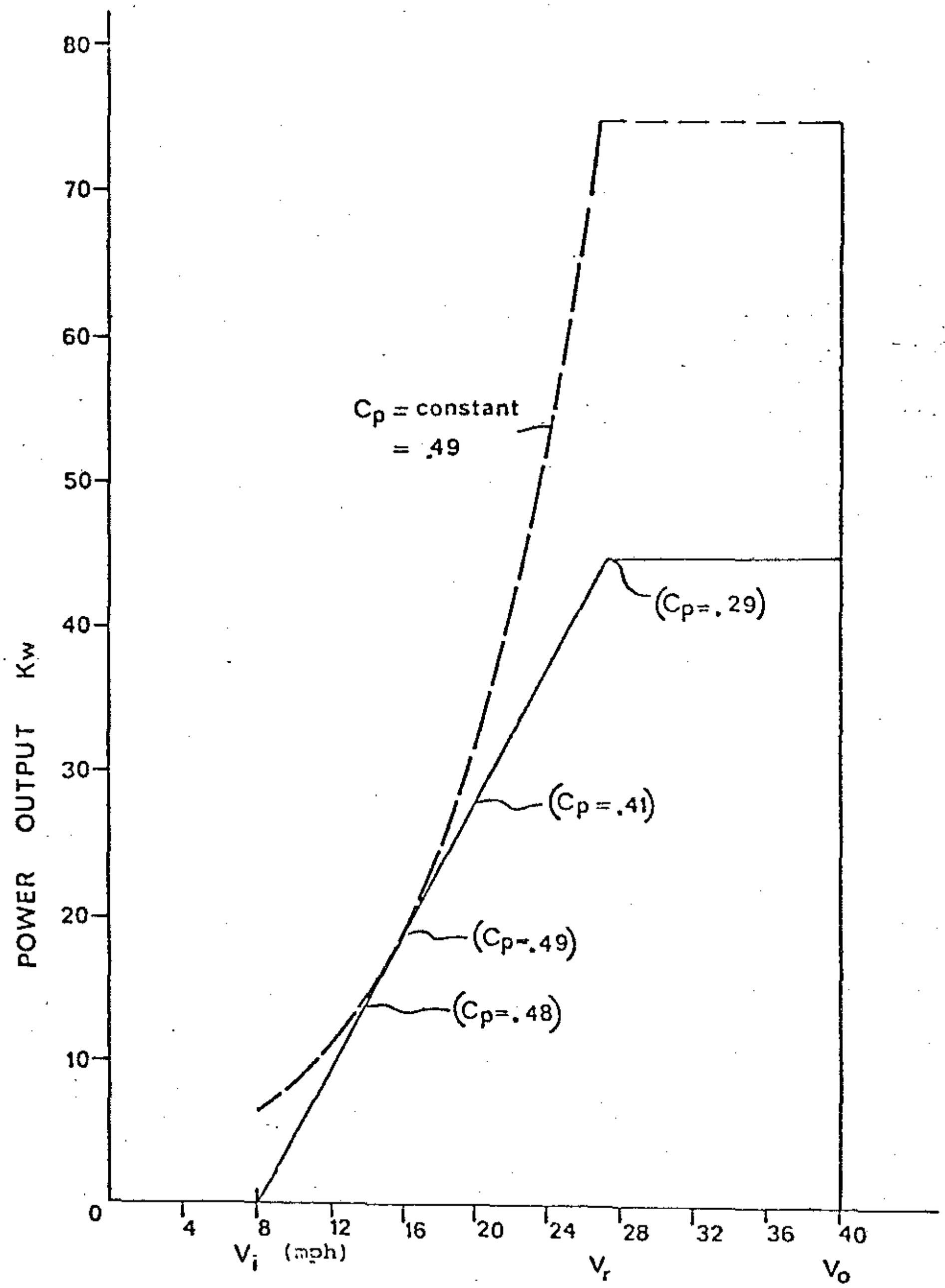


Figure 4 STRAIGHT LINE (VARIABLE C_p) OUTPUT AND IDEAL (CONSTANT C_p) OUTPUT OF ENERGY DEVELOPMENT CO. WTG

A comparison of the yearly energy output, AKWh, for the EDC 45 kW and the "ideal" VSCF EDC WTG is shown in Table 4. The ideal VSCF produces between 20% and 40% more yearly energy than the VSCF EDC design.

5.2 WTG Economics

Breakeven electric energy costs and payback times for two basic utility interconnected WTG are summarized below. The calculations are based on the formulas outline in Appendix B.4 (see Appendix B.4 for definition of economic variables). The two commercially available WTG are (1) a 45 kW Energy Development Company (EDC) WTG and (2) a 15 kW Environmental Energies Allison WTG. Results for a modified Energy Development Company WTG called the Michigan Department of Transportation (MDOT) WTG are also presented. This system, the 40 kW double output induction generator concept, is then compared with the standard EDC WTG. The basic assumptions used in the economic analysis are:

(1) a 10% interest rate r_1 on initial capital investment

(2) general inflation rate r_2 = .07 or 7%

(3) electric energy escalation rate r_3 = .01 or 10%

(4) AOM = .01IC

(5) N=0 is the beginning of 1979

(6) the WTG have zero salvage value at the end of the system lifetime

(7) there are no property taxes or insurance paid on the WTG installations

(8) the WTG machine characteristics were determined from information supplied by the manufacturers. They are summarized below

Energy Development Company WTG

V_i = 3 m/s

V_o = 18 m/s

V_r = 12 m/s

P_r = 45 kW

TABLE 4*

COMPARISON BETWEEN THE ENERGY DEVELOPMENT MACHINE AND AN IDEAL VARIABLE SPEED CONSTANT FREQUENCY MACHINE**

<v>	C_f	Pr	AkWh	C_f	Pr	AkWh	%Increase
10mph	.12	45	45,300	.095	75	62,400	32%
12	.22	45	86,700	.159	75	104,500	20%
14	.29	45	115,100	.237	75	155,900	35%
16	.37	45	145,800	.312	75	205,000	40%

Thus certain DOIG religious may be in improvement over the current WTG that are now available. The economic and the actual field performance of the VSCF-DOIG religious should be studied further.

---

*< v > - Site Average Wind Speed

C_f - Capacity Factor

AkWh - Annual Power Output in kWh

** Data tabulation provided by Edward Conley of M.S.U.

Environmental Energies Allison (EEA) WTG
(from curves supplied)

$V_i = 4$ m/s
$V_o = 20.5$ m/s
$V_r = 13.5$ m/s
$P_r = 18.5$ kW

(9) The WTG installed costs were determined from quotes supplied by the manufacturers. The installed costs are:

(1) EDC WTG : IC = $36,300

(2) EEA WTG : IC = $40,000

(3) MDOT EDC WTG : IC = $45,100

(10) three hub height average wind speeds were assumed: (1) 5.5 m/s (~12.3 mph), (2) 6.0 m/s (~13.4 mph) and (3) 6.5 m/s (~14.5 mph). It was assumed that the average winds at the Niles site were similar to the 11 mph (at 21 feet) average winds at the South Bend, Indiana airport. Height correcting these winds to 50-70 feet with a .14 to .28 power law resulted in the 5.5 - 6.5 m/s hub height average winds.

(11) WTG availability* is assumed to be 90% for all calculations.

Tables 5 and 6 display the results of the calculations. The breakeven levelized and present electric energy cost, $\bar{y}$ and y_o^{-1} respectively, were determined by assuming that no energy is sold back to the utility. The breakeven present energy cost y_o^{-1} was calculated by assuming that 20% of the AKWH was sold back to the utility at 1/3 the customer price.

The initial cost, IC, for the MDOT WTG was determined from cost estimates for design modifications to a standard EDC WTG. The major modifications are: (1) a change from a standard 45 kW induction generator to a 40 kW double output induction generator, (2) the additional electronic controls for the second generator output and (3) engineering development costs.

---

*See Appendix for definition of availability.

Table 5. Environmental Energies Allison WTG

Site average wind speed (m/s)	AKWH (kwh/yr)	IC/AKWH*	$\bar{y}$ \$/kWH	y_o \$/kWH	y_o' \$/kWH
5.5	33,100	1.21	0.16	.069	0.079
6.0	39,400	1.02	0.13	0.59	0.068
6.5	45,700	.875	0.11	.050	0.057

*Total installed cost (IC) = \$40,000 including \$1,000 for an isolation transformer.

Energy Development Company-Standard 45kw WTG

Site average wind speed (m/s)	AKWH (kwh/yr)	IC/AKWH**	$\bar{y}$ \$/kWH	y_o \$/kWH	y_o' \$/kWH
5.5	80,000	0.45	0.062	0.026	0.03
6.0	94,000	0.39	0.053	0.022	0.026
6.5	107,600	0.33	0.045	0.019	0.022

**Total installed cost (IC) = \$36,300

Energy Development Company - Michigan Department of Transportation redesign

Site average wind speed (m/s)	AKWH* (kwh/yr)	IC/AKWH**	$\bar{y}$ \$/kWH	y_o \$/kWH	y_o' \$/kWH
5.5	91,400	0.45	0.067	0.028	0.032
6.0	107,200	0.42	0.057	0.024	0.027
6.5	123,000	0.37	0.051	0.021	0.025

*Assumes a 90% WTG availability for the double output induction generator

**Total installed cost (IC) = \$45,100

Table 6. Payback Time in Years for the Energy Development WTG

Electrical Energy Price (1979) kWh	Average Wind Speed (Hub Height) 5.5m/s	6.0m/s	6.5m/s
3¢	17 (18)*	15	12
4¢	13 (14)*	11	9
5¢	10 (11)*	8	7
6¢	8 (9)*	7	< 7
7¢	7	<7	< 7

*The Michigan Department of Transportation Redesign

Payback Time in Years for the Environmental Energies WTG

Electrical Energy Price (1979)kWh	Average Wind Speed (Hub Height) 5.5m/s	6.0m/s	6.5m/s
3¢	52	43	36
4¢	37	31	26
5¢	29	24	20
6¢	24	20	16
7¢	20	17	14

In order to improve WTG economics an increase in IC must be compensated for by an increase in AKWH. This can be seen clearly from equation (10) of Appendix B.4. For a given application CRF and G_1 are independent of the WTG design and breakeven costs are directly proportional to the ratio IC/AKWH. Thus an increase in IC from $36,300 to $45,100 (an approximate 25% increase in IC) for the MDOT WTG must be compensated by at least a 25% increase in AKWH to be a cost effective design change.

The results summarized in Tables 5 and 6 clearly indicate that unless the AOM is much larger than the $400/year assumed, the standard EDC WTG is an economically attractive machine even in the 5.5 m/s hub height winds and the Niles electric energy costs of 3.5 - 4.5¢/kWH ($ 1979). Payback times are as low as 8-12 years and would be lower if some WTG salvage value were assumed.

Throughout most of upper and lower Michigan electric utility rates are usually 4¢/kWh or greater and average yearly winds are 10 mph or greater at 21 feet elevation. Thus the results of this study can be generalized to suggest that MDOT and other government agencies should investigate the application of utility interconnected WTG for new and existing facilities.

6.0 Data Acquisition System

Power and weather data information will be recorded at the Niles solar demonstration project. The data will be taken at each stage of the solar conversion process as well as at the loads and utility interfaces. Specific parameters to be recorded include temperature, radiation, and wind speed along with the necessary electrical sensors to map the total energy flow. Variable sampling time is planned for this data acquisition system since some signals, such as temperature, will change slowly, other, such as wind speed, will change very rapidly, and still others such as fan and hand dryer loads will change in a random manner. Therefore, the data recording system must have the capability of sampling every few seconds on some signals and a few times an hour on others. Normally, the data will be summed (integrated) over many sample times (and averaged where applicable) to reduce the quantity of data. Monthly, daily and hourly totals (or averages) will be recorded on magnetic disk.

Rapidly changing signals, like the wind speed, are not adequately described by an average or running total. To accommodate data of this type, the data acquisition system will have the capability of generating frequency of occurence tables. This is accomplished by quantizing the data range of the signal and recording the occurence of samples in each interval. In this way a statistical description of the signal is developed which contains the information in compact form.

The data acquisition program operation, including updating frequency of occurence tables, adding or removing data items, and changing sampling intervals, will be controlled via the DEC writer terminal located at Niles. This does not require a computer operator. A remote data link by phone line to Lansing is planned to allow the retrieval of data. It should be possible to control the minicomputer by the remote communication link.

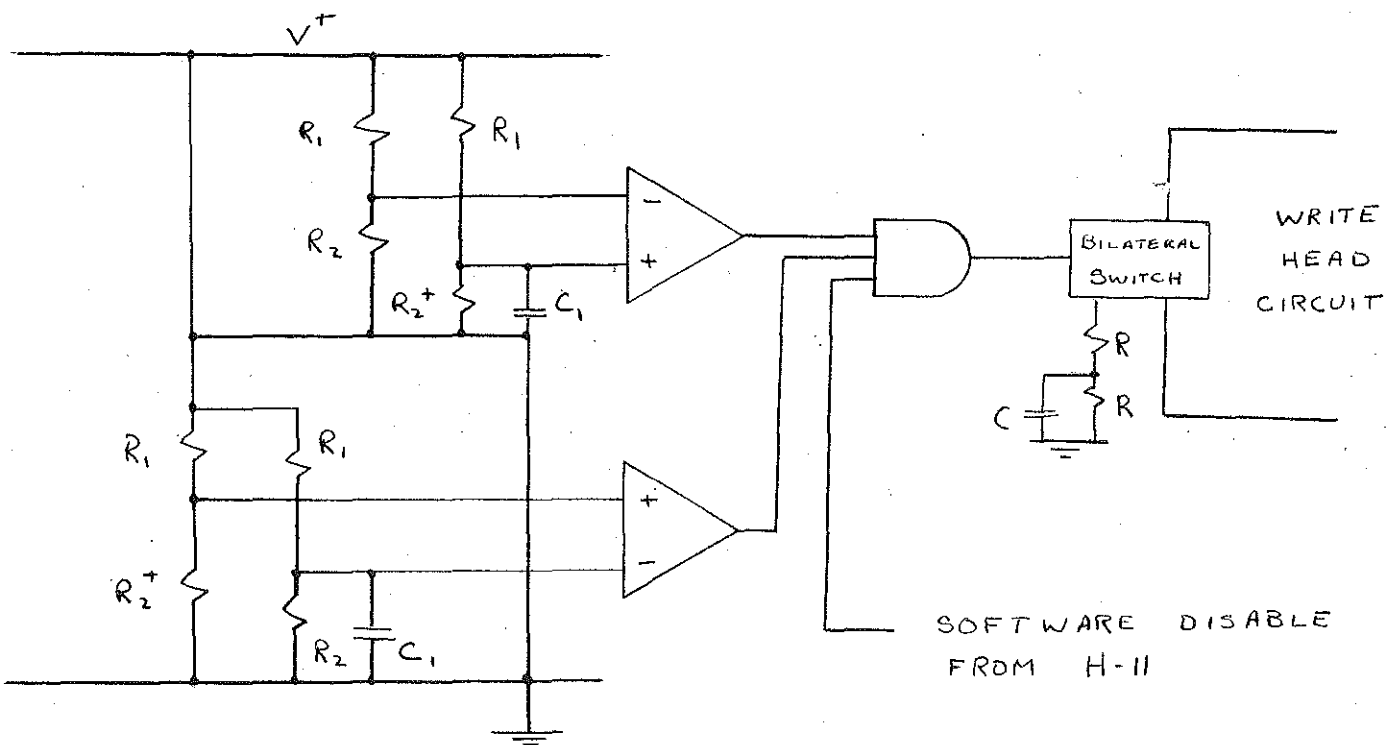
The Heathkit minicomputer purchased to handle data acquisition is also responsible for display of appropriate information for public viewing. The computer system consists of the central processor, a dual floppy disk drive with operating system, 20 kilo bytes of read/write memeory, a DEC writer teletypewriter and three additional interface boards (two parallel interfaces for data acquisition and display and a serial interface for remote access). The central processor, a 16-bit PDP-11, and the software operating system are supplied by Digital Electronics Corporation.

Several portions of the operating system--the monitor, file handler, editor, BASIC interpreter, macro expander, macro library, assembler, loader and emulator--have been tested successfully. In addition, three test programs have been developed to familiarize the Highway Department with the system (see Appendix C.2 for description of the test programs). The first program, IOTEST, is an input/output exercise. The second program, ASCIII, includes subroutines to perform the ASCII to binary input conversion and binary to ASCII output conversion. The third program, FLOP1, investigates the problem of information loss during power up/power down in the floppy drive. This routine evaluates control of information loss. FLOP1 was used several times to test the floppy for data loss during power down and power up. No permanent damage was detected on the disk. A more sophisticated test examining the contents of a given sector on the desired track should be developed. A possible hardware solution to the power down/power up data loss is shown in Figure 5. If an appropriate DC voltage V^+ can be found in the floppy, the write-head disable circuit should be useful.

The data acquisition hardware shown in block diagram form on Figure 6 consists of an analog to digital converter (ADC), sensor multiplexing, and logic to perform signal handshaking with the parallel interface module (PIM). The data acquisition PIM has a base address of 177350_8 and an interrupt vector to 370_8. This interrupt vector may need to be altered, if the system loader does not load into the first 400_8 words of memory.

The data acquisition transmitter control and status register (XCSR) and receiver control and status register (RCSR) are accessed through memory locations 177350_8 and 177354_8 respectively. The PIM assembly manual or system operation manual should be consulted for the XCSR and RCSR bit assignments. When the proper bits have been set in XCSR and RCSR, the data acquisition hardware can be operated in a handshake mode as described below.

FLOPPY WRITE-HEAD DISABLE CIRCUIT



$R_2^+ \approx (1.2)\ R_2$

THE BILATERAL SWITCH IS A SINGLE-POLE, DOUBLE-THROW SEMICONDUCTOR SWITCH. THE 4016 IS A CMOS VERSION.

WHEN THERE IS A 20% CHANGE IN V^+, ONE OF THE COMPARATORS FORCES THE AND GATE LOW WHICH SWITCHES THE R-C INTO THE WRITE HEAD CIRCUIT. THIS SHOULD SMOOTH OUT SUPPLY TRANSIENTS.

Figure 5

DATA ACQUISITION HARDWARE

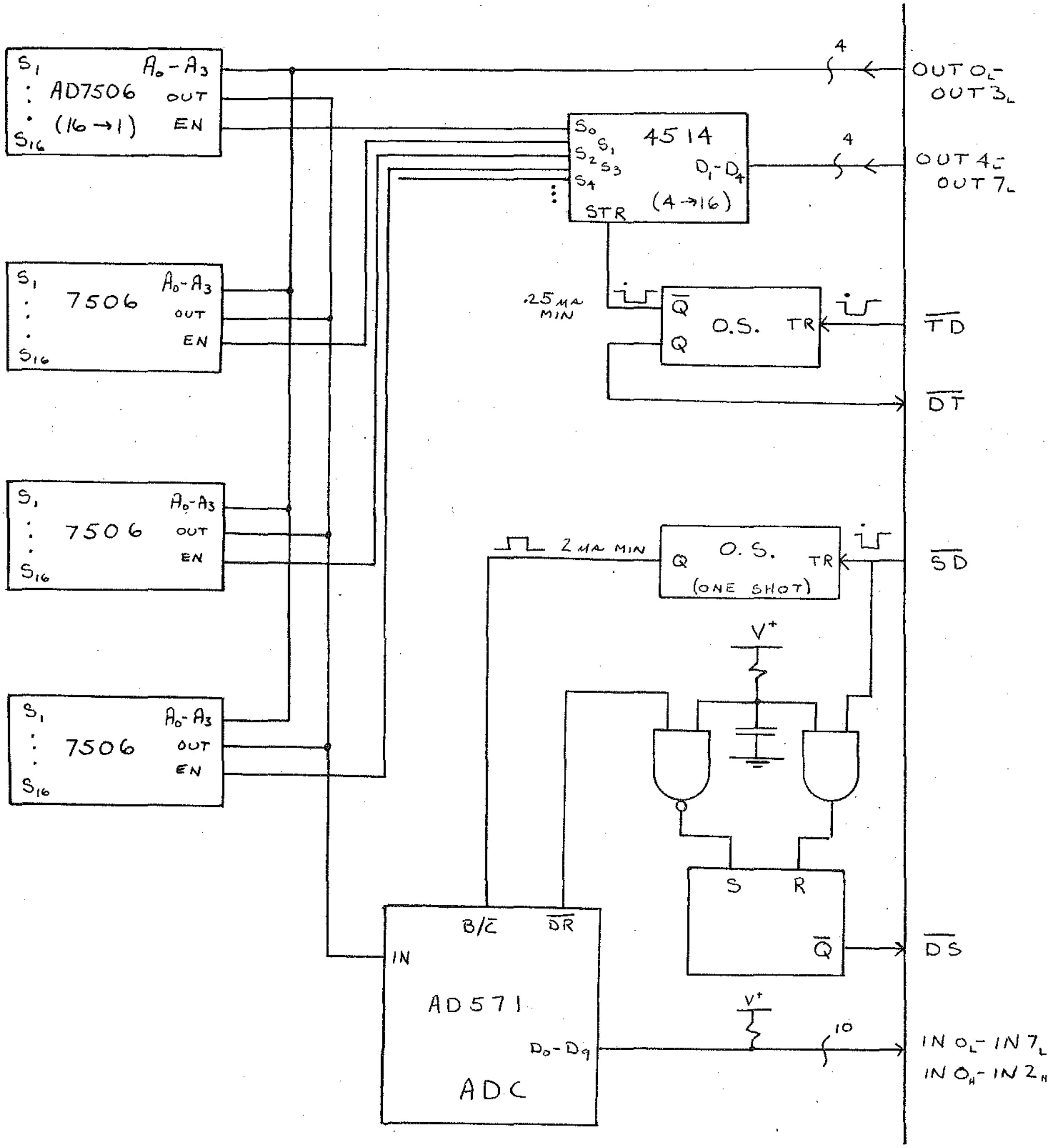


Figure 6

In the idle state, TAKE DATA L ($\overline{TD}$) and SEND DATA L ($\overline{SD}$) (signals from the computer) are high (negated) while DATA TAKEN L ($\overline{DT}$) and DATA SENT L ($\overline{DS}$) (signals to the computer from hardware) are low (asserted). To obtain a data sample the following two steps are necessary: (1) sensor addressing, and (2) sample conversion.

To address a specific sensor the computer writes that sensor's address into the transmitter data buffer register (XDBR) at memory location 177352_8. The $\overline{TD}$ signal from the PIM goes low (true) which triggers the one-shot that resets $\overline{DT}$ high momentarily, and strobes the sensor address into the 4514 latch/decoder (these latches are actually unnecessary since the XDBR is also a set of latches; however, if needed, the strobe pulse is available). The high level on $\overline{DT}$ (from Q of one-shot) resets $\overline{TD}$ high acknowledging that the sensor address has been taken. Eight bits are output to the data acquisition hardware through the low byte of XDBR. The lower four bits address all the (AD7506) 16 to 1 analog multiplexers. The upper four bits are decoded by the 4514 (a 4 to 16 decoder) which enables one of the four multiplexers, connecting its analog output (from the addressed sensor) to the ADC (AD571). Since only 4 of the 16 outputs from the 4515 are used, there are 12 lines available for expansion or additional data devices such as a digital clock.

After the appropriate sensor is addressed, the computer requests data to be converted and sent through the RCSR. The receiver interrupt should be enabled at the same time.

When $\overline{SD}$ is asserted low by the PIM, the one-shot is fired which initiates the analog to digital conversion. The low level on $\overline{SD}$ also resets the RS flip-flop which drives $\overline{DS}$ high. The $\overline{DS}$ high signal acknowledges the data request so that PIM resets $\overline{SD}$ high. The ADC requires fifteen to thirty microseconds and will generate an interrupt when $\overline{\text{DATA READY}}$ from the ADC sets the flip-flop sending $\overline{DS}$ low (true). The data is now available through the RDBR (address 177356_8).

The converted data requires ten bits of the 16-bit RDBR. If other types of data are to be sent through the same RDBR, the ADC output lines could be multiplexed. However, since they are already tri-state, additional blanking logic on the BLANK/$\overline{\text{CONVERT}}$ input (of the ADC) would allow these outputs to be wired-ORed.

The details of the public display at the Niles demonstration project has not yet been finalized. The MSU team, however, strongly recommends that at least a portion of the display utilize a television monitor (CRT). The CRT is a familiar form of display which provides flexibility in choice of parameters to be displayed.

The CRT display would allow several screens of information to be presented. One screen, for example, could show the current status of the system including the environmental conditions, the power being generated by each source, the power consumed, and the energy savings. Another screen could explain the operation of the Niles solar energy system. The display could also be used to inform citizens about new innovations in energy and transportation. Thus, the TV monitor display offers the MDOT a direct communication with the traveling public.

The best feature of the CRT display is its flexibility. Being under computer control, the entire display format, or just small parts of it, can be changed. This allows the display to be updated by discarding outdated features and adding new information.

7.0 Conclusions

This report has described the significant factors involved in the design, analysis and economics of a multi-faceted solar system that includes two wind turbines, a photovoltaic array, a Trombe wall, an earth sheltered structure and a minicomputer data acquisition system. The active solar electric systems, wind and photovoltaic, are interfaced to the utility via a synchronous line commutated inverter. Specific solar and control components have been chosen for implementation in the Niles solar demonstration facility. Based on the chosen components along with manufacturers specifications and environmental conditions the performance of each component is evaluated. Economics are attached to each component of the solar system.

The diversity of energy designs for the rest station provide the opportunity for hands-on experience in the most promising of the decentralized alternatives. In addition to the education to be afforded to MDOT, energy savings will accrue, some at favorable costs, energy conservation will be encouraged and positive public visibility will be provided.

Appendix A

A.1 Letter sent to photovoltaic panel suppliers

A.2 Solar sensors, interface circuits suppliers and costs

Appendix A

This appendix contains information on the photovoltaic system including solar cell specifications, proposed sensor list, and the interface circuits necessary to scale the sensor outputs to the range 0-10 V_{dc}. The sensor list is referenced to the system configuration in Figure A.1. Several points should be noted:

(1) The size and type of load sensor is not specified (since the loads have not been specified)

(2) No sensors have been included to examine the harmonic output of the synchronous inverters. This will probably require further consultation with the Indiana-Michigan Public Utility.

(3) The OSI PC5 series AC power transducers have several output options including 0-10 V_{dc} (option C) which costs $66. If the interfaces were designed inhouse for these transducers a reasonable savings could result. Further, if the interface were multiplexed a significant saving would be realized.

(4) The interface circuit for current transducers (interface 4) is not included. This interface requires both an excitation supply circuit and an output filtering circuit. Depending upon circuit settling time it may be possible to multiplex between the sensors.

(5) The OSI CT-L line of current transducers is available with a split-core (for $50). This makes these current transducers moveable.

SYSTEM CONFIGURATION

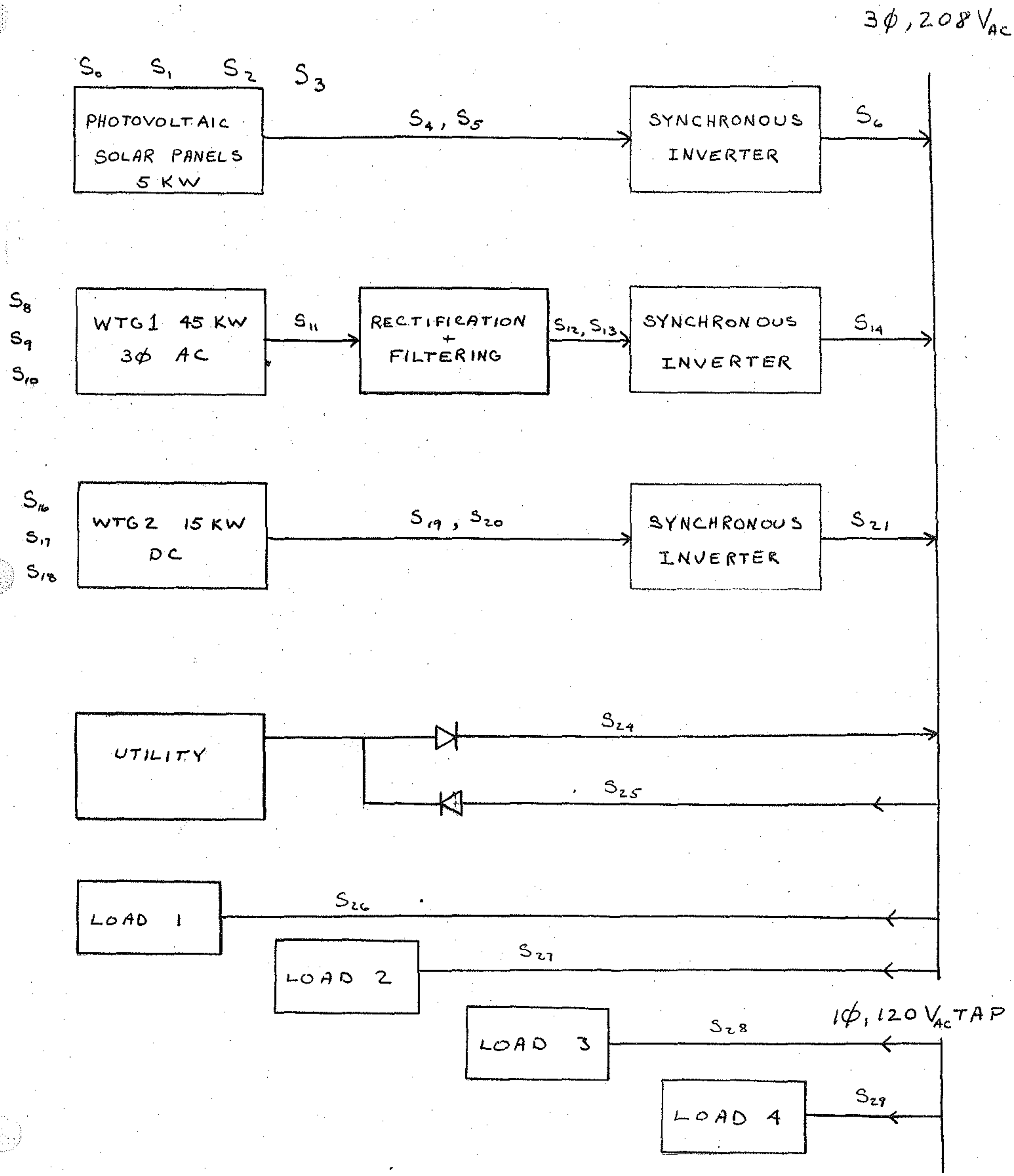


Figure A.1

Appendix A.1

WILLIAM G. MILLIKEN, GOVERNOR

DEPARTMENT OF TRANSPORTATION

TRANSPORTATION BUILDING, 425 WEST OTTAWA PHONE 517-373-2090

POST OFFICE BOX 30050, LANSING, MICHIGAN 48909

JOHN P. WOODFORD, DIRECTOR

Research Laboratory Section
Testing and Research Laboratory
Secondary Governmental Complex
P. O. Box 30049
Lansing, Michigan 48909

The Michigan Department of Transportation is planning to let contracts for the construction of a public information and highway rest station on US-31 south of Niles, Michigan. The project is to include solar photovoltaic and wind energy electric generation systems. The intent of this project is to supplement the energy supplied to the facility in addition to providing extensive visibility to the public. The objectives include promotion of energy alternatives, energy conservation and experience in the performance of solar and wind systems in Michigan. This information will provide a basis for future decisions involving energy generation for other highway purposes.

The rest area design include the solar photovoltaic and wind energy systems is being developed with technical assistance from the Department of Electrical Engineering of Michigan State University.

The completion date for this public information center is projected to be June 1, 1980. The solar system should be installed in the spring of 1980.

This Department is requesting proposals from selected solar photovoltaic manufacturers for a 5Kw solar array.

The Department is not required to accept competitive bids because of the experimental nature of the system. The technical and cost proposals received will be evaluated by Department personnel and Michigan State University engineering faculty.

MICHIGAN THE GREAT LAKE STATE

An Equal Opportunity Employer

The specific parameters which are to be addressed in your cost and technical proposal, are outlined on the following pages. Additional strengths or advantages of your solar products or company which may contribute to system performance should be indicated.

The deadline receiving proposals is May 15, 1979. The selection of the successful manufacturer will be made by June 15, 1979.

Sincerely,

TESTING AND RESEARCH DIVISION

L. T. Oehler, Engineer of Research
Research Laboratory Section

A.1 Continued

SOLAR VOLTAIC GENERATION SYSTEM

Project Description

The solar photovoltaic (SPVS) array is to be mounted on top of a flat roofed, 4,800 square foot building located in a flat, treeless area. The building is to be set into a sloping landform with access on the south side. The roof will therefore be approximately at grade level along three sides.

The 5 kW is to be interconnected with electric utility lines. The building heating, cooling, hot water and lighting is to be supplied by the SPVS, wind turbine generators and the electric utility. There are no current plans for energy storage using hot water or batteries.

A 5 kW (peak power) photovoltaic array with passive reflecting sheets at 18° elevation of equal dimension to the active cell array (for increased energy collection) is to be mounted on the building roof. The specification of 5 kW peak power refers to maximum power available with normally incident light of 1 kW/meter^2 and 42°C. This, however, does not include contributions from the reflector.

The solar array is to be interfaced to the utility grid using a "Gemini" inverter. The inverter will be coupled into a single phase 110 volt supply inside the facility.

The nominal surface area allotted to the active solar cell array is 800 square feet although lower area requirements are desirable (if dense cell packing is possible at reasonable costs).

In addition to the 5 kW solar cell array, two wind turbines providing up to 60 kW (peak) will be interfaced to a three phase 240 volt utility grid using another "Gemini" inverter and induction generator.

Required Information

The following topics require specific manufacturer descriptons and comments:

(1) Basic description of SPVS and its interconnection to the electric utility. (Photographs if available.) Describe module size, mounting requirements, weight and module interconnection recommendations to interface to the Gemini inverter.

(2) State the cost of the solar array including "Gemini" inverter, mounting hardware and wiring.

(3) Discuss the need for and cost of power factor correction if required for connection to the electric utility line.

(4) Discuss warranties available for the solar array, components and system performance.

(5) Discuss installation requirements, methods and estimated costs. Detail your role (supplier) and ours (Michigan Department of Transportation) in the installation, supervision of installation and final system checkout and start up. Indicate if costs for supervision and checkout are included in quoted costs.

(6) Indicate surface area required for 5 kW (peak) not including reflector contribution.

(7) Recommend optimum angle of elevation for solar array for the Niles site.

(8) Detail delivery schedule, estimate of costs and methods of shipping to the Niles site.

(9) Describe the maintenance requirements and procedures for isolating non-working modules.

(10) Detail wind load ratings for the roof mounted modules.

(11) Discuss the availability of factor interfaced systems including the "Gemini" inverter for peak power tracking.

(12) Describe any lightning protection provided or required for the solar array.

(13) Comment on any safety procedures required for utility personnel, Department employees and site visitors (solar array will be at ground level).

Questions may be directed to:

Jes Asmussen
Department of Electrical Engineering & Systems Science
Michigan State University
East Lansing, Michigan 48824
Phone: (517) 355-4620

H. Roland Zapp
Department of Electrical Engineering & Systems Science
Michigan State University
East Lansing, Michigan 48824
Phone: (517) 355-5230

(Leave message with MSU secretary) (517) 355-5066

OR

Leo DeFrain, Michigan Department of Transportation
Phone: (517) 322-1632

Appendix A.2

SENSORS FOR PHOTOVOLTAIC ARRAY

SENSOR #	SENSOR Name & Part Number	Output	Quantity Measured	Interface #	Interface Cost	Sensor Cost	Total Cost
S0	Eppley Model 8-48 Global Pyranometer	11 V/Wm^{-2}	Total Solar Radiation incident on the solar panels	$1-S_0$	19.25	590.00	609.25
S1	Eppley Model NIP Normal Incidence Pyranometer Plus Model ST-1 Solar Tracker	8 V/Wm^{-2}	Direct radiation incident on the solar panels	$1-S_1$	19.25	890.00 790.00	1699.25
S2	Analog Devices AD590KH Temperature transducer	1 A/°K	Ambient temperature in vicinity of solar cells	$2-S_2$	22.50	6.00	28.50
S3	AD590KH	1 A/°K	Temperature of solar cells	$2-S_3$	22.50	6.00	28.50
S4	Resistor Divider Network	$0-10V_{DC}$	DC Voltage output from solar cells	$3-S_4$	15.00	–	15.00
S5	Ohio Semitronics CT50LTT Current Transducer	.4mV/A	DC current output from solar cells	$4-S_5$		104.60	104.60
S6	OSI PC5-23C 3Ø, 208 V_{AC} Power Transducer	$0-10V_{DC}$	3Ø AC Power inverted by the Gemini, excluding harmonics	-	66.00	191.10	257.10

SENSOR/MULTIPLEXER INTERFACES

Interface 1 (I_1)

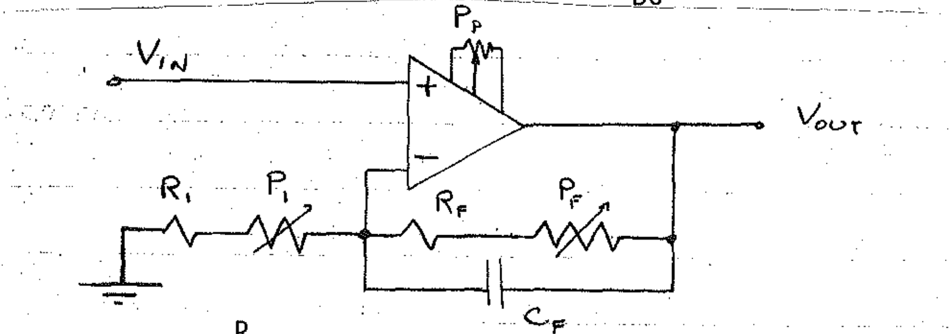
Sensors: Eppley Model 8-48, Model NIP

Sensor Input: (Normal) Incident Solar Radiation

Sensor Output: (8μV) 11μV/W m^{-2} Nominal

(Interface Input)

Interface Output: All Interface Outputs are 0-10 V_{DC}



$$V_{OUT} = V_{IN} \left(\frac{R_F}{R_1} + 1\right)\left(\frac{1}{1+SC_FR_F}\right)$$

Power: ±15 V_{DC}

	Cost	(8-48) I_1-S_0	I_1-S_{36}	(NIP) I_1-S_1	
Op Amp	11.25*	AD517KH	AD517KH	AD517KH	
R_1	.50	1KΩ	1KΩ	820Ω	5% metal film
P_1	2.00	500Ω	500Ω	500Ω	cermet
R_F	.50	1.2MΩ	1.2MΩ	1.2MΩ	
P_F	2.00	50KΩ	50KΩ	50KΩ	
C_F	1.00	5μF	5μF	5μF	20% tantalum
P_P	2.00	10KΩ	10KΩ	10KΩ	
TOTAL	19.25				

Interface Numbers: I_1-S_0, I_1-S_{36}, I_1-S_1

*Quantities of 1-21 (25 @ 9.50 = 237.50)

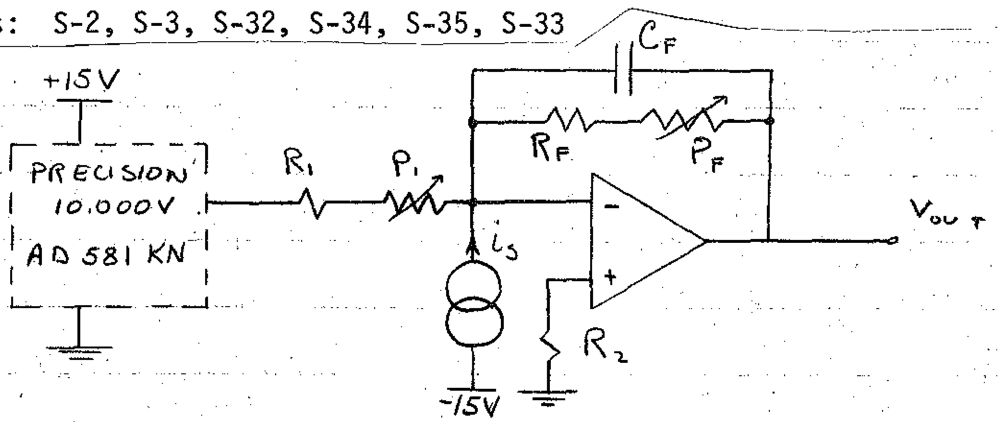
Interface 2 (I_2)

Sensors: AD 590 KH

Sensor Input: Temperature -55°C to +73°C (128°C swing)

Sensor Output: 1μA/°K

Interfaces: S-2, S-3, S-32, S-34, S-35, S-33



$$V_{OUT} = R_F(i_s - \frac{10}{R_1})(1 + \frac{1}{SC_FR_F})$$

Power: $\pm$15 V_{DC}, 10.000 V_{DC} (581) = \$12.45

I_2-S_{33}			COST	
	Op Amp	AD517KH	11.25	
	R_1	39KΩ+1.8KΩ	1.00	
	P_1	500Ω	2.00	cermat
39KΩ	R_F	68KΩ+10KΩ	1.00	2% metal film
	P_F	500KΩ	2.00	
	C_F	25μF	1.00	20% tantalum
	R_2	2.2K	.10	10% carbon
	P_R	10KΩ	2.00	
		TOTAL	20.35	+ 1/6 (12.45) ≈ 22.50

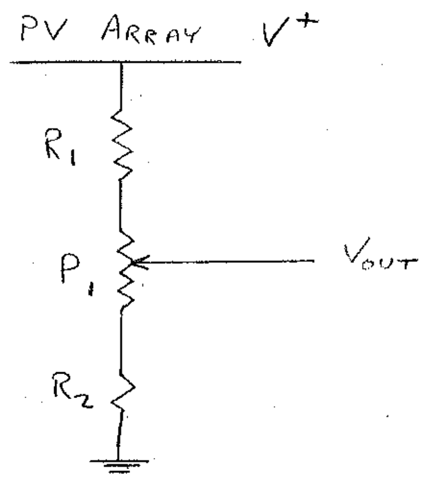
R_1 = 41.118KΩ $\pm$ 170Ω (1°C) $\pm$ 40Ω (1 LSB)

R_F = 78.067KΩ $\pm$ 614Ω (1°C) $\pm$ 80Ω (1LSB)

INTERFACE 3 (I_3)

"Sensor" Output: PV Array DC Voltage Out

INTERFACES: S-4, S-12, S-19



R_1	2% metal film	- 1.5MΩ	.50
R_2	" " "	- 47 KΩ	.50
P_2	cermat	- 10 KΩ	2.00
		TOTAL	3.00

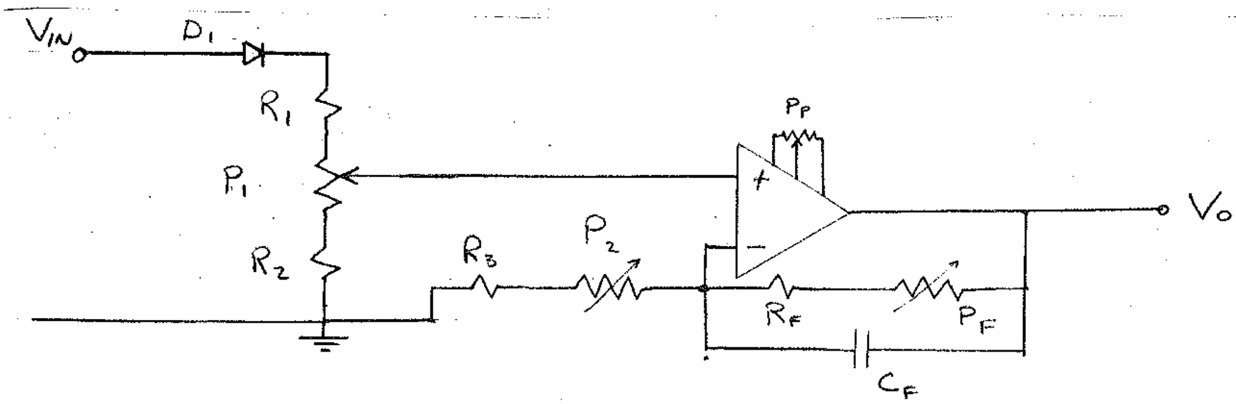
INTERFACE 5 (I_5)

Sensor: Weather Measure Skyvane

Sensor Input: Wind Speed (0 - 128 mph)

Sensor Output: .22 V_{ac}/mph

Interfaces: S-8, S-16



$$V_o = (V_{in} - V_{d1}) \frac{R_2}{R_1+R_2} \left(\frac{R_F}{R_3} + 1\right)\left(\frac{1}{1+sC_FR_F}\right)$$

Power: ± 15 V_{DC}

Part		Cost
OP AMP	AD517KH	11.25
D_1	IN4001	1.00
R_1	56KΩ	.50
R_2	10KΩ5%	.50
P_1	2KΩ	2.00
R_3	100KΩ	.50
P_2	10K Ω	2.00
R_F	100KΩ	.50
P_F	10KΩ	2.00
C_F	2μF	1.00
P_P	10KΩ	2.00
	TOTAL	23.25

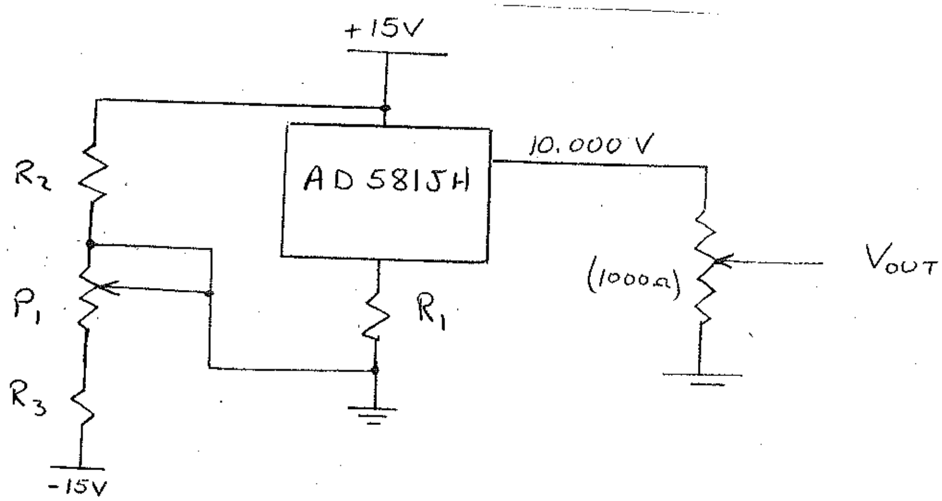
INTERFACE 6 (I_6)

Sensor: Weather Measure Skyvane W1D2-P-AC/540

Sensor Input: Wind Direction

Sensor Output: 0-1000Ω

Interfaces: S-9, S-17



Power: ± 15 V_{DC}

	Part	Cost
	AD481JH	4.95
R_1	22Ω	.10
R_2	6.8KΩ	.10
R_3	4.3KΩ	.10
P_1	10KΩ	2.00
	TOTAL	7.25

Appendix B

B.1 Letter sent to WTG suppliers

B.2 Wind sensors, interface circuits, costs

B.3 Fundamental design options for utility inter-connected wind turbine generators

B.4 Economic formulation for WTG systems

Appendix B

This appendix contains information on the wind turbine systems including a required manufacturers WTG specifications, proposed sensor list, and the interface circuits necessary to scale the sensor outputs to the range 0-10 V_{dc} for conditioning for computer input. The sensor list is referenced to the notation of the system configuration of Figure A.1 (Appendix A).

Appendix B.1

STATE OF MICHIGAN

WILLIAM G. MILLIKEN, GOVERNOR

DEPARTMENT OF TRANSPORTATION

TRANSPORTATION BUILDING, 425 WEST OTTAWA PHONE 517-373-2090
POST OFFICE BOX 30050, LANSING, MICHIGAN 48909

JOHN P. WOODFORD, DIRECTOR

Research Laboratory Section
Testing and Research Laboratory
Secondary Governmental Complex
P. O. Box 30049
Lansing, Michigan

The Michigan Department of Transportation is planning to let contracts for the construction of a public information and highway rest station on US-31, south of Niles, Michigan. The project is to include solar photovoltaic and wind energy electric generation systems. The intent of this project is to supplement the energy supplied to the facility in addition to providing extensive visibility to the public. The objectives include promotion of energy alternatives, energy conservation and experience in the performance of solar and wind systems in Michigan. This information will provide a basis for future decisions involving energy generation for other highway purposes.

The rest area design, including the solar photovoltaic and wind energy systems, is being developed with technical assistance from the Department of Electrical Engineering of Michigan State University.

The completion date for this public information center is projected to be June 1, 1980. The wind turbine generators should be installed in the spring of 1980.

This Department is requesting proposals from selected wind machine manufacturers for two utility interconnected wind turbine generators (no energy storage.) Two utility interconnected concepts are to be evaluated:

(1) a wind turbine generator (WTG) using a 3-phase induction generator system, and
(2) a WTG with direct current output for connection to a line commutated synchronous inverter.

The Department is not required, because of the experimental nature of this equipment, to accept competitive bids. The technical and cost proposals received will be evaluated by Department personnel and Michigan State University engineering faculty. It is expected that the two WTG systems will be purchased from different manufacturers but one manufacturer may submit proposals for both system concepts.

The specific parameters which are to be addressed in your cost and technical proposal are outlined on the following pages. Additional strengths or advantages of your WTG or company which may contribute to system performance should be indicated.

The deadline for receiving proposals is May 15, 1979. Selection of the successful proposal will be made by june 15, 1979.

Sincerely,

TESTING AND RESEARCH DIVISION

L. T. Oehler, Engineer of Research
Research Laboratory Section

B.1 Continued

WIND TURBINE GENERATORS

Project Description

It is expected that two utility interconnected wind turbine generators (WTG) will be demonstrated at the Niles, Michigan information and rest station. These are:

(1) WTG with 3-phase induction generator (single phase generator may also be acceptable)

(2) WTG with D.C. output which is to be connected to a line commutated synchronous inverter ("Gemini" inverter)

These WTG are to be located in a flat treeless area located about 350 feet on either side of the facility's 4,800 square foot building. The WTG along with a 5 kW photovoltaic array is to be interconnected with electric utility lines. The building heating, cooling, hot water and lighting is to be supplied by the WTG, the photovoltaic system and the electric utility. There are no current plans for energy storage using hot water or batteries.

MINIMUM REQUIREMENTS OF EACH SYSTEM

(1) Power output of 8 kW in a 20 mph wind (it is expected that rated power and rated velocity may be higher for some designs).

(2) Tower height 50-70 feet.

(3) Total kWh/year must be greater than or equal to 18,000 kWh/year in a hub height yearly average wind speed of 11 mph.

(4) Must be able to be connected either to a single phase 110 volt AC line or a three phase 240 volt AC line.

(5) Each WTG manufacturer must provide the entire WTG system, i.e., the WTG, tower, batteries if required, and inverter required for connection to the utility lines.

Required Information

The following topics require specific manufacturer descriptions and comments:

(1) Basic description of the WTG and the WTG-utility interconnect system (photographs if available). Specify: WTG rated power, rated wind velocity, cut-in velocity, cut-out velocity, blade diameter, weight of generator and blades, tower, maximum blade rpm, high wind shut down and protection. If batteries or inverters are supplied as part of the design, specify the power, voltage and amp-hour ratings. Provide WTG power output versus wind speed characteristics and estimate yearly WTG system energy output for hub height average winds of 11 mph to 12.5 mph.

(2) State the cost of the WTG, tower and if required, the cost of batteries, inverters and any other needed system components (filters, relays, etc.). Also, foundation requirements for tower.

(3) Discuss the need for and costs of power factor correction if inverters are required for connection to the electric utility lines.

(4) Describe warranties available for WTG components or system performance.

(5) Indicate size of open area required for optimum performance of WTG.

(6) Describe installation requirements, methods and estimated costs. Detail your role (supplier) and ours (Michigan Department of Transportation) in the installation, supervision of installation and final system checkout and start-up. Indicate if costs for supervision and checkout are included in quoted costs.

(7) Detail delivery schedule, estimate of costs and methods of shipping the WTG system to the Niles, Michigan site.

(8) Describe the maintenance requirements and procedures.

(9) Describe the relaying provided (or that must be provided if not furnished) for WTG shut-down in case of utility power failure and describe the start-up procedures for the WTG after return of utility power. Indicate whether these operations are automatic or what manual switching is required.

(10) Discuss provisions available for control of load current between the WTG and the utility.

(11) Describe the lightning protection provided in the WTG system, i.e., the generator, tower, batteries, electronic circuits and utility. The description should include protection in case of (a) direct hit to the tower by lightning and (b) a hit on the utility line.

(12) Comment on any special safety precautions required for utility personnel, Department employees and site visitors.

Questions may be directed to:

Jes Asmussen or H. Roland Zapp
Department of Electrical Engineering & Systems Science
Michigan State University
East Lansing, Michigan 48824
Phone: J. Asmussen (517) 355-4620
H. R. Zapp (517) 355-5230
(leave message with MSU secretary, (517) 355-5066)

OR

Leo DeFrain, Michigan Department of Transportation
Phone: (517) 322-1632

Appendix B.2

Sensor Manufacturers

Analog Devices
RT 1 Industrial Park
P. O. Box 280
Norwood, MA 02062 (617) 329-4700

Local Distributor:

A. P. Associates
496 Ann Arbor Trail
Plymouth, MI 48170 (313) 459-1200

Eppley Laboratory, Inc.
12 Sheffield Ave.
Newport, RI 02840 (401) 847-1020

Weather Measure Corp.
P. O. Box 41257 Toll Free (800) 824-5811
Sacramento, CA 95841 (916) 481-7565 2
3
4

Ohio Semitronics, Inc.
1205 Chesapeake Ave.
Columbus, OH 43212 (614) 486-9561

Appendix B.2

SENSORS FOR WTG1 - EDC's 45 Kw

SENSOR #	Name & Part Number	Output	Quantity Measured	Interface #	Interface Cost	Sensor Cost	Total Cost
S_8	Weather Measure W102-P/AC Skyvane I Wind Sensor	.22 V_{AC}/MPH	Wind speed incident on WTG1	5-S_8	13.25		
S_9 S_{10}	(Dual Wiper Wind Direction Sensor)	0-1000 0-500	Wind Direction At WTG1, 0°-540°	6-S_9	7.25	795.00	
S_{11}	OSI PC5-62C 3Ø, 240V_{AC} Power Transducer	0-10 V_{DC}	AC Power Produced by WTG1	(C)	66.00	261.80	
S_{12}	Resistor Voltage Divider	0-10 V_{DC}	DC Voltage after Rectification	3-S_{12}	15.00	-	15.00
S_{13}	OSI CT200LTT Current Transducer	.25mV/A	DC Current after Rectification	4-S_{13}		116.30	116.30
S_{14}	OSI PC5-62C 3Ø, 240 V_{AC}, 40kW Power Transducer	0-10 V_{DC}	AC Power after Gemini Inversion	(C)	66.00	261.80	

SENSOR FOR WTG2 - ENVIRONMENTAL ENERGIES - 15Kw

SENSOR #	SENSOR Name & Part Number	Output	Quantity Measured	Interface #	Interface Cost	Sensor Cost	Total Cost
S_{16}	Weather Measure W102-P/AC Skyvane I Wind Sensor	$.22V_{AC}$/MPH	Wind Speed At WTG2	5-S_{16}	23.25		
S_{17} S_{18}	(Dual Wiper Wind Direction Sensor)	0-1000 0-500	Wind Direction at WTG2; 0°-540°	6-S_{17}	7.25	795.00	
S_{19}	Resistor Voltage Divider	$0\text{-}10V_{DC}$	DC Output of WTG2	3-S_{19}	15.00	-	15.00
S_{20}	OSI CT 50LTT Current Transducer	.5mV/A	DC Current Out of WTG2	4-S_{20}		104.60	
S_{21}	OSI PC5-53C 3Ø, 240V, 20Kw Power Transducer	$0\text{-}10V_{DC}$	AC Power After Gemini Inversion	(C)	66.00	261.80	327.80

Appendix B.3

Fundamental Design Options for Utility Interconnected Wind Turbine Generators

Utility interconnected wind turbine generators are electromechanical devices that transform the energy in the wind into utility grade electricity. This transformation is not a one-step process, but consists of several interdependent conversion processes. These usually are:

(1) The conversion of wind energy into rotating shaft mechanical energy

(2) The conversion of mechanical energy into electrical energy.

(3) The conversion of electrical energy into utility grade, constant frequency 60 Hz electricity.

These conversion processes occur in the three WTG subsystems - aerodynamic, mechanical and electrical - shown in the block diagram of Figure B.3-1. The instantaneous power in the wind P_w for a swept area A is given by

$$P_w = 1/2\rho\ V^3 A \qquad (B-1)$$

where

ρ = air density

V = wind velocity

A = area swept by the WTG blades.

Wind power is converted into shaft power or mechanical power, P_m, with an efficiency, denoted by $C_p(v)$, which is function of wind velocity, i.e.

$$P_m = C_p(V) P_w = 1/2\ \rho V^3\ A\ C\rho(V) \qquad (B-2)$$

Shaft mechanical power that is converted into useful electrical power is given by

$$P_e = P_m\ \eta_m \eta_g = 1/2\ \ \rho V^3 A C_p(V)\eta_m(V)\ \ \eta g(V) \qquad (B-3)$$

When η_m = mechanical drive train conversion efficiency

η_g = electrical conversions efficiency.

The relationship between input wind speed and output useful electrical power described in equation (B-3) is

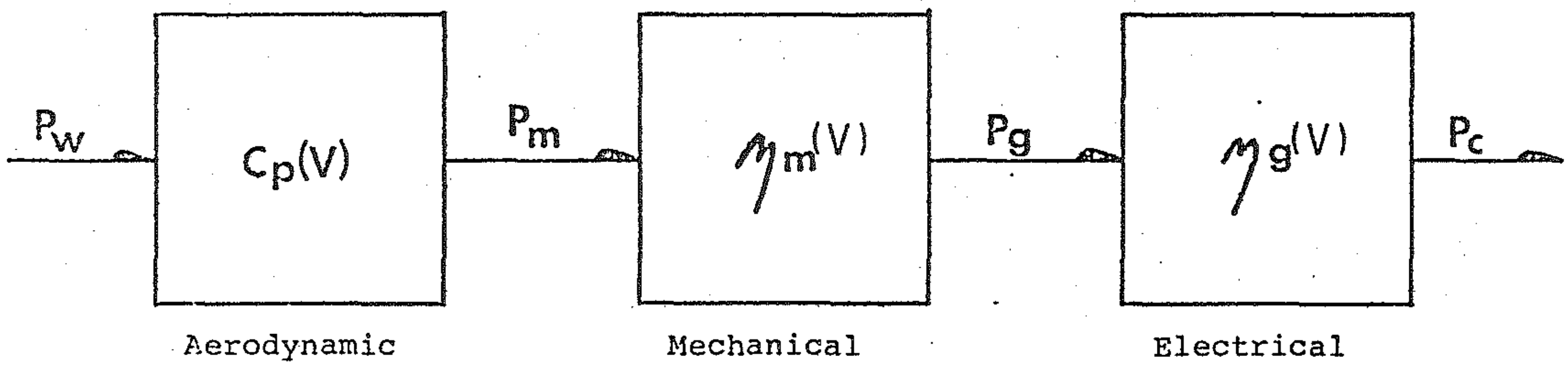


Figure B.3-1 WTG SUBSYSTEMS

usually called the machine characteristic. This machine characteristic is a function of wind speed, i.e.,

$$P\ (V) = P_e = 1/2\rho V^3 A\ C_p(V)\ \eta_m(V)\ \eta_g(V) \qquad \text{(B-4)}$$

If the actual frequency distribution of the wind at the site is known, then an estimate of the wind turbine expected average power is given by

$$P_{ave} = \int_0^\infty P(V)\rho(V)dV \qquad \text{(B-5)}$$

where

P_{ave} = The average power output of the wind turbine
$P(V)$ = The machine characteristic
$\rho(V)$ = The frequency distribution (probability density distribution) of wind speed is based on hourly average wind speed often is and usually can be approximated by a Weibull or Rayleigh distribution.

The annual energy output of a WTG is expressed as

$$AKWH = 8760 \int_0^\infty P(V)\rho(V)dV \qquad \text{(B-6)}$$

The design of a device that efficiently converts wind energy into utility electricity at a low cost is complex because (1) the various conversion steps and subsystems are interactive, i.e., the design of one subsystem impacts on the other subsystem; (2) the energy input, wind energy, is random in time and cannot be controlled, only understood, and (3) the utility line load imposes voltage current, power factor and frequency constraints on electric energy transfer.

All utility interconnected WTG systems must produce 60 Hz electricity (in contrast to battery charging WTG that produce direct current electricity). Thus all utility interconnected WTG are constant output frequency (CF) systems. However, the input aerodynamic subsystem, can be either a constant rotation speed (CS) or a variable rotational (VS) design speed. Thus wind turbine generators can be grouped into two basic different design concepts:

(1) Variable-Speed Constant-Frequency (VSCF) Systems and (2) Constant-Speed Constant-Frequency (CSCF) Systems. These options together with a number of specific designs are classified in Figure B.3-2.

The aerodynamic subsystem converts the power in the wind, P_w into mechanical power, P_m, usually with a two- or three-blade rotor rotating on either a vertical or horizontal axis. The efficiency of this conversion process, denoted by $C_p(V)$, is called the power coefficient. This coefficient depends on the type and shape of the rotor blades and also on the ratio of blade tip speed to wind speed. Typical examples of the dependence of C_p on the tip speed ratio for several blade types are shown in Figure B.3-3.

If the shaft speed, ω, is held constant and the turbine rated speed corresponds to the maximum value of C_p, then increasing or decreasing wind speed will result in decreasing C_p. However, if the rotor speed is allowed to vary with wind speed so that the ratio of blade tip speed to wind speed is held constant, then maximum C_p can be realized for all operating wind speeds. Constant or variable rotor speed defines the two basic aerodynamic systems. In the constant rpm (or constant-speed, CS) system the rotor rpm is held constant by continually adjusting blade pitch and/or by the generator type. The variable speed WTG allows the rotor rpm to vary. Thus in theory a variable speed machine can be designed that allows the rotor rm to vary in proportion to wind speed holding the tip speed ratio constant and resulting in (C_{pmax}) for most of the operating region between cut-in and rated wind speeds.

The most common design concept for large machines is the CSCF System, a concept that is also becoming popular among designers of small machines. The choice of either a synchronous generator or a squirrel-cage induction generator for the utility grid interface imposes the constant speed requirement on the aerodynamic system (see Figure B.3-2). For example,

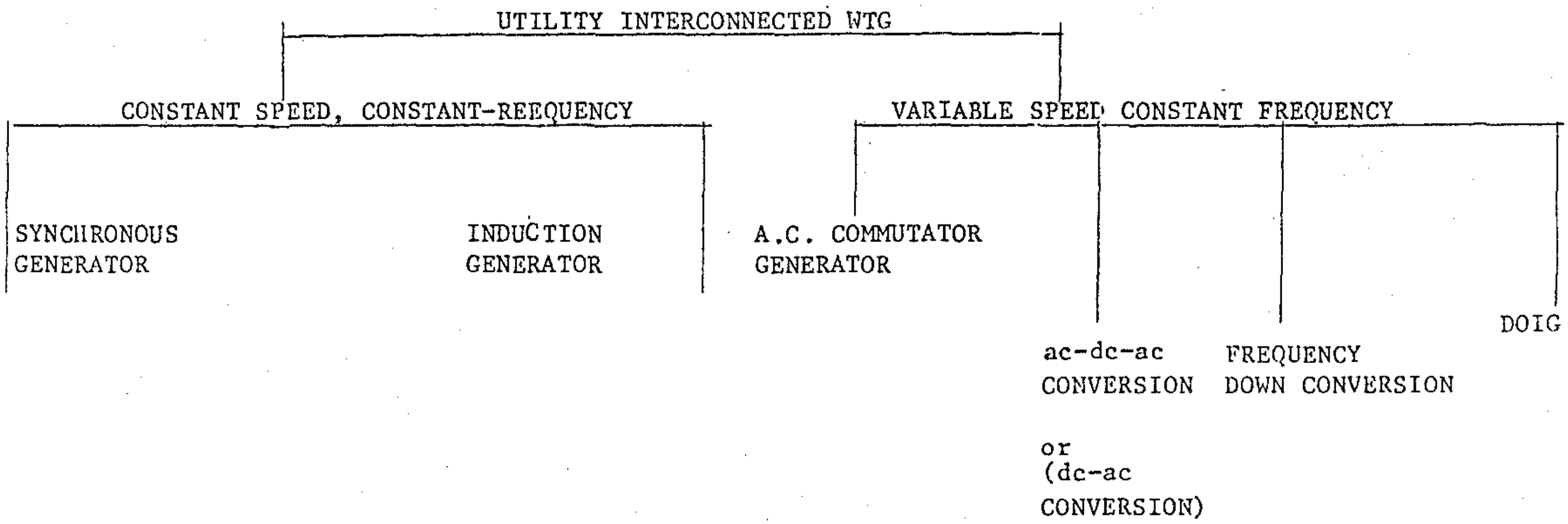


Figure B. 3-2 CLASSIFICATION OF UTILITY INTERCONNECTED DESIGN OPTIONS

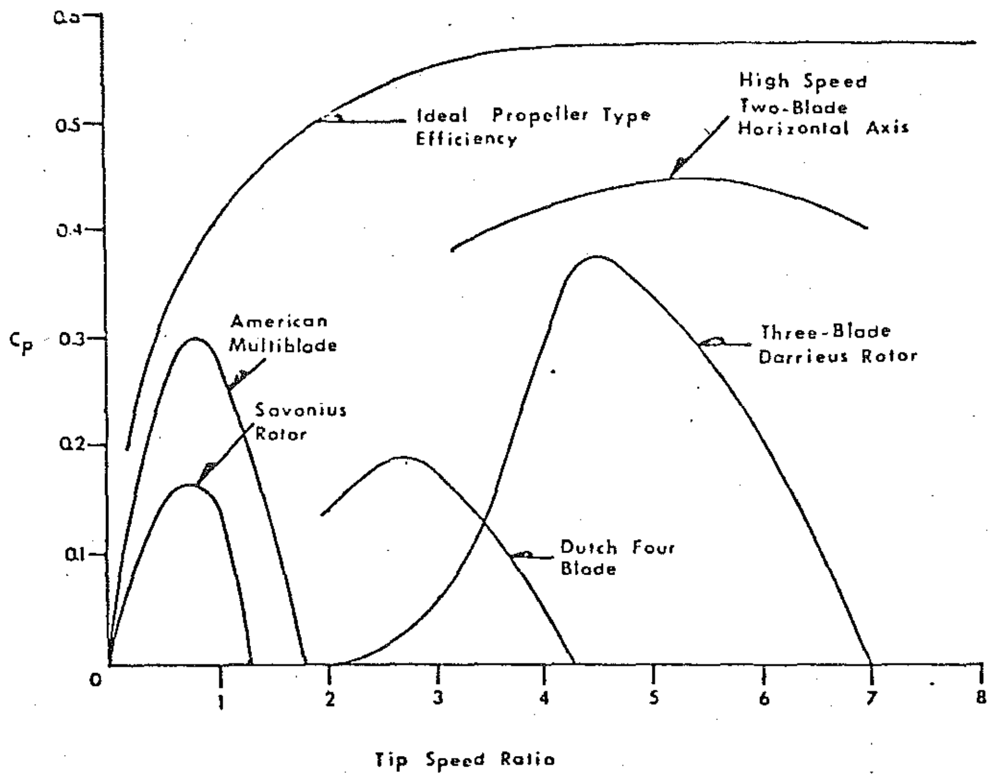


Figure B.3-3 C_p VARIATION WITH TIP SPEED RATIO FOR VARIOUS WTG TYPES if a synchronous generator is chosen, then a control system is required to control the pitch so that rapid wind gusts are not transmitted to the utility grid. The pitch control system must be sensitive enough to damp out the wind gust transients to prevent the WTG output from becoming unstable. These controls are expensive and add to the overall system complexity.

The squirrel-cage induction generator has the advantage of low cost and not necessarily requiring expensive blade pitch controls. However, it has the disadvantages of operating at a low power factor and capturing less energy from a given wind regime than the synchronous machine.

A number of CSCF designs have attempted to avoid the costs and complexity of pitch controls by using an induction generator. Examples of this type of design are the Danish Gedser 200kW machine (1,2) and the commercially available Enertech 1500, 1.5kW WTG. These machines have fixed-pitch blades and the operating rpm is chosen to maximize aerodynamic efficiency at one particular wind speed. Therefore, C_p decreases at all other wind speeds. A pitch control, although it can be used, is not required for this type of application if the blade airfoil is designed so that the efficiency falls off rapidly when the wind velocity exceeds a certain value, usually the rated wind velocity.

Several methods to achieve VSCF WTG operation have been suggested and analyzed (3-6). A number of important concepts are mentioned in Figure B.3-2 and described in Figures B.3-4 through B.3-7. In each of these systems complexity is increased by the requirement of additional electronic controls and in several cases special electrical generators. However, many of these systems will not require pitch controls.

A number of commercially available small machines use the AC-DC-AC (or CD-AC) conversion concept. Many of these machines are copies of old battery charging designs adapted for utility interconnection with line commutated synchronous.

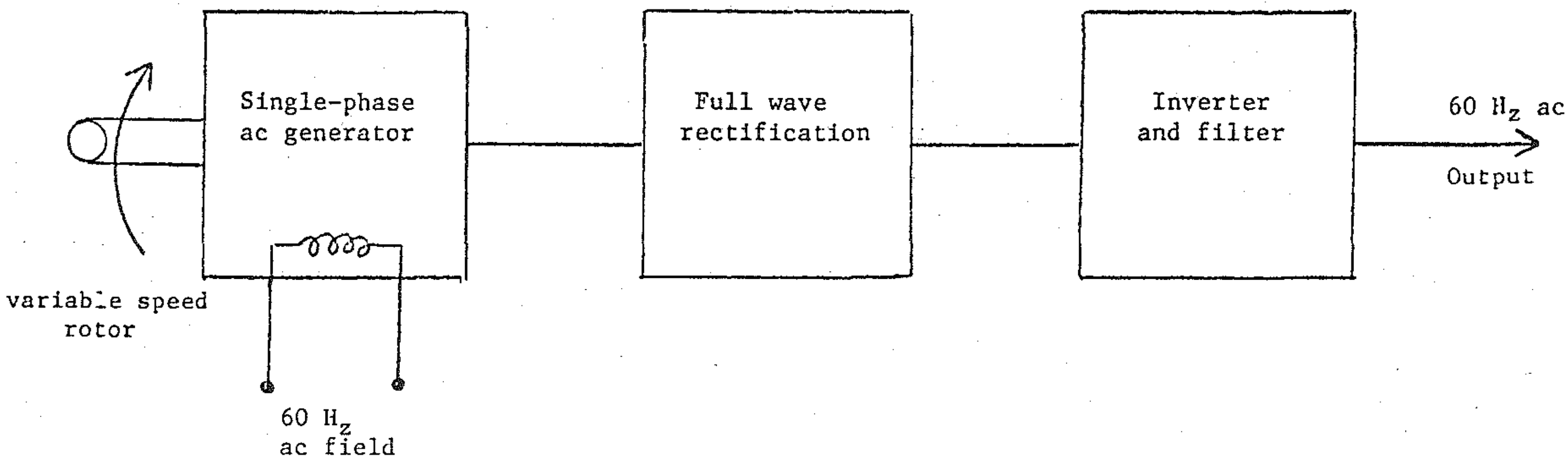


FIGURE B. 3-4 FREQUENCY-DOWN-CONVERSION VSCF SYSTEM

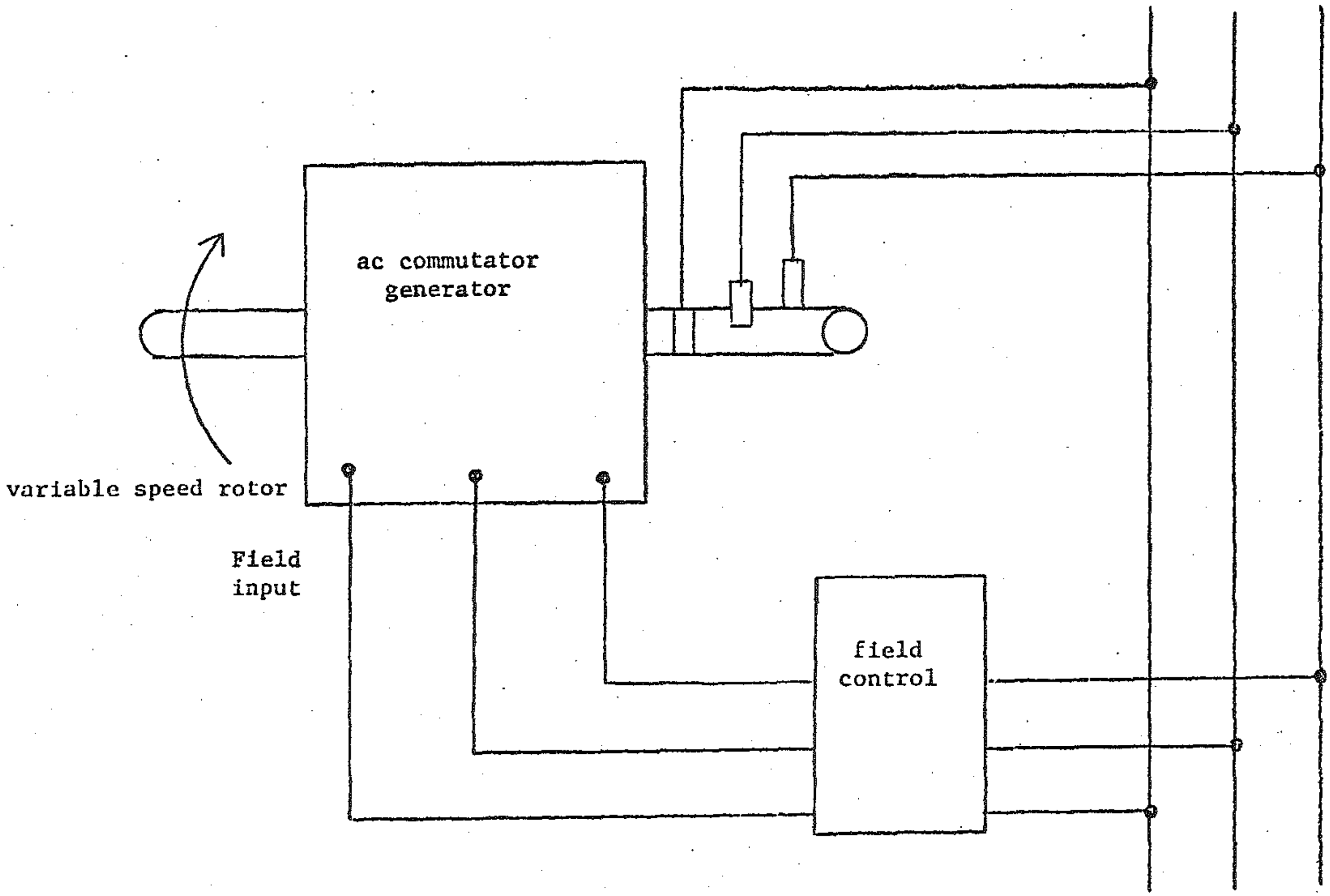


FIGURE B.-3-5 AC COMMUTATOR GENERATOR VSCF SYSTEM

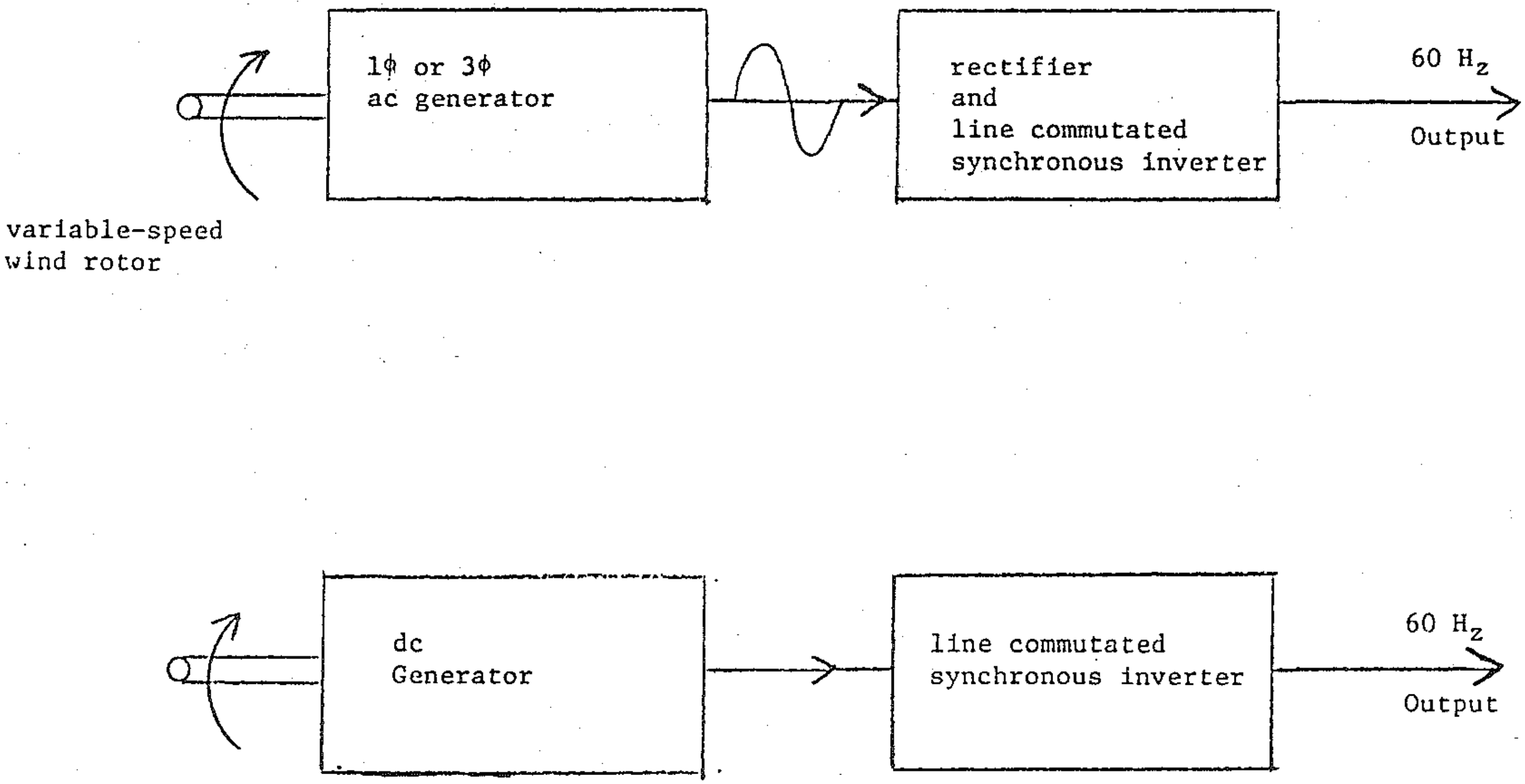


FIGURE B. 3-6 AC-DC-AC CONVERSION

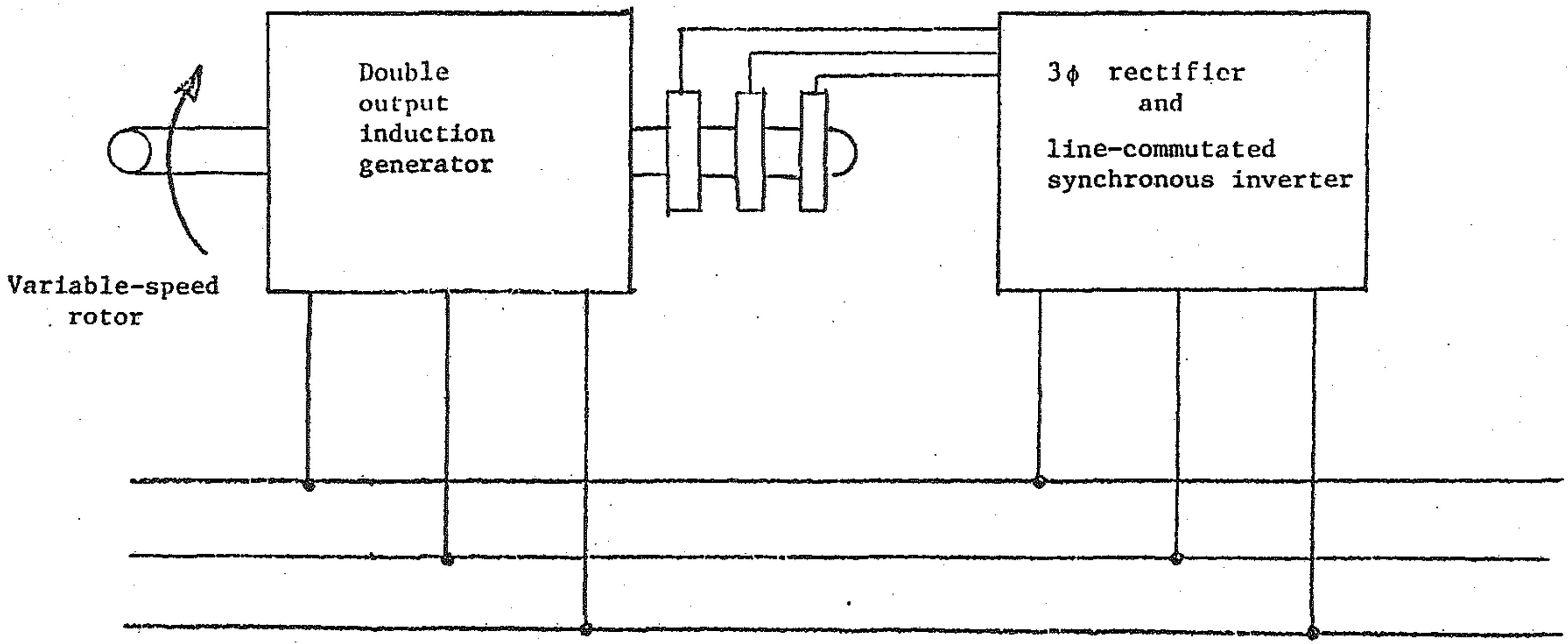


FIGURE B. 3-7 DOUBLE OUTPUT INDUCTION GENERATOR AND CONTROL

Thus, despite the utility interconnection, these machines may not be optimum VSCF designs and probably do not operate at efficient C_p over the entire region between cut-in and rated wind speeds.

A comparison between the CSCF and the VSCF concepts is made in the following simplified example. Assume that both the VSCF and CSCF concepts have the same blade design, an equal overall system efficiency of .40 at rated speed, and an identical power output above rated wind speed until cut-out. Typical machine characteristics of each design are shown in Figure B.3-8. Between cut-in and rated winds there are important performance differences in the two concepts. The VSCF machine operates at a constant tip speed ratio resulting in a constant efficiency in this region. This is an idealization and cannot be achieved exactly in a "real life" design. Thus the design depicted in Figure B.3-8 will be identified as an "ideal VSCF" design. The efficiency of the CSCF WTG on the other hand must decrease as the wind speed decreases as shown in Figure B.3-8. It is evident from these curves that these two basic aerodynamic designs concepts will yield different energy outputs in the same wind regime.

The theoretical calculations (B-7) show that the ideal VSCF system can produce as much as 25% to 30% more annual energy than CSCF designs. In particular, the NASA-Lewis 100 kW wind turbine could produce 30% more energy at its wind site if it would be changed to a VSCF design. Equivalently, the ratings can be lowered by 30% implying a lighter tower, etc., and cost savings. A conclusion of this study (6) indicates that the 25-30% increase in annual energy estimate are sufficient to justify research efforts into VSCF designs for both large and small machines.

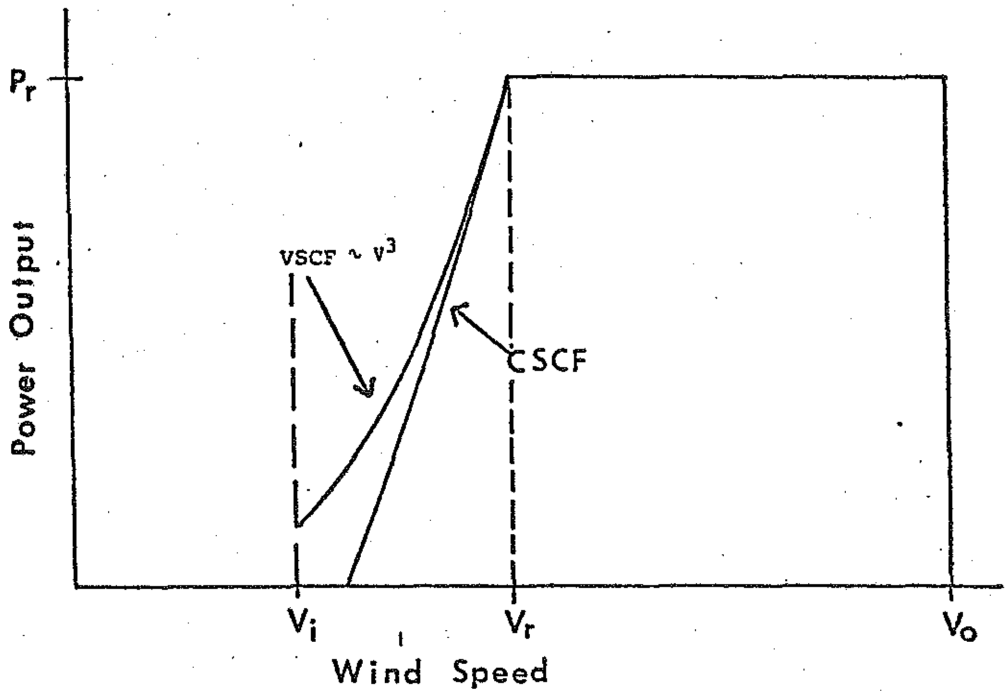


Figure B. 3-8 TYPICAL OUTPUT FOR VARIABLE SPEED CONSTANT FREQUENCY AND CONSTANT SPEED CONSTANT FREQUENCY WTGS

References

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5. D. K. Reitan, "A Progress Report on Employing a Non-Synchronous AC/DC/AC Link in a Wind-Power Application," Proceedings of the Second Biennial Conference and Workshop on Wind Energy Conversion Systems, June 9, 1979, p. 290.

6. T. S. Jayadev, "Novel Electric Generator Schemes for Wind Power Plants," Proceeding of the Second Biennial Conference and Workshop on Wind Energy Conversion Systems, June 9, 1978, p. 298.

7. M. Martinez-Sanchez, A Performance Comparison Between Constant RPM and Constant Velocity Ratio Operation of a Windmill, ERDA/NSF/00826-78/2 MIT, February 15, 1976.

Appendix B.4

Economic Formulation for WTG Systems

The economics of any size WTG can be determined by the following basic equation:

$$S_N = (1+r_1)^N IC + \frac{1 - \left(\frac{1+r_1}{1+r_2}\right)^N}{1 - \left(\frac{1+r_1}{1+r_2}\right)} [1+r_2]^N AOM$$

$$- \frac{(1+r_1)^N - 1}{r_1} \bar{y}\ AKWH \qquad \text{(B-4)}$$

where the following are defined

- N = lifetime of the system (in this study N is expressed in years)
- IC = total initial installed (turn-key) system cost in \$ at time N=0
- AOM = annual operation and maintenance cost in \$ at time N=0
- $AKWH$ = total useful annual kilowatt-hours produced by the WTG system per payment period
- r_1 = interest rate on the initial capital investment
- r_2 = general inflation rate
- r_3 = electric energy escalation rate
- S_N = balance left of the initial capital investment after N years
- $\bar{y}$ = levelized electric energy costs over the useful lifetime of the WTG

The left hand side of the above equation, the balance S_N of the initial capital investment after N periods, is equal to three separate terms. The first term represents the initial capital investment compounded at an interest rate r_1 for N periods. The second term represents the operation and maintenance (O&M) costs added to the initial capital investment each period. The third term, expressed in terms of levelized cost $\bar{y}$, is the amount of money received over the lifetime N by selling the energy produced by the WTG system (i.e., total dollars supplied by wind system over N years is $\bar{y}$ N AKWH). When solving for breakeven levelized energy costs for payback time, N, set $S_N = 0$.

The levelized energy cost, $\bar{y}$, is that price per unit of energy which, if held constant over the life of the system, would recover all the costs of owning and operating the system. The last term in equation (B-4) can also be expressed in terms of present costs of energy, y_o, i.e.,

$$\frac{1 - \left(\frac{1+r_1}{1+r_3}\right)^N}{1 - \left(\frac{1+r_1}{1+r_3}\right)} (1+r_3)^N y_o (AKWH) \qquad \text{(B-4.2)}$$

where

r_3 = the electrical energy escalation rate

y_o = the cost of electrical energy at time N=0

When S_N=0 then equation (B-4.2) must equal the last term in equation (B-4.1) or

$$\frac{1 - \left(\frac{1+r_1}{1+r_3}\right)^N}{1 - \left(\frac{1+r_1}{1+r_3}\right)} (1+r_3)^N y_o (AKWH) = \frac{(1+r_1)^N - 1}{r_1} \bar{y} \text{ AKWH} \qquad \text{(B-4.3)}$$

Solving for $\bar{y}$ yields the relationship between y_o and $\bar{y}$:

$$\bar{y} = y_o \text{ CRF } G_2 \qquad \text{(B-4.4)}$$

where

$$\text{CRF} = \frac{r_1}{1 - (1+r_1)^{-N}} = \text{capital recovery factor}$$

$$G_2 = \left(\frac{1+r_3}{r_1-r_3}\right)\left(1 - \left(\frac{1+r_3}{1+r_1}\right)^N\right.$$

Solving equation (B-4.1) for levelized energy cost (S_n=0) yields

$$\bar{y} = \frac{CRF}{AKWH}\,[IC + G_1 AOM] \tag{B-4.5}$$

where

$$G_1 = \left[\left(\frac{1+r_2}{r_1-r_2}\right)\left(1 - \left(\frac{1+r_2}{1+r_1}\right)^N\right)\right].$$

Equation (B-4.5) can also be expressed as

$$\bar{y} = \frac{CRF\ IC}{AKWH} + \frac{AOM\ LF}{AKWH} \tag{B-4.6}$$

where

$LF = G_1 CRF$ = a levelizing constant that adjusts the O and M cost for inflation over the system lifetime.

Thus, WTG costs are made up of five different factors: (1) IC, (2) CRF (called fixed charge rate, FCR, when property taxes and insurance are included), (3) AOM, (4) LF and (5) AKWH. Several of these are WTG dependent while others are essentially application dependent. IC and AKWH are usually dominated by WTG machine design and manufacturing costs while LF and FCR are application dependent. AOM is dependent on the WTG design but is also strongly dependent on the local labor rates, etc. Each of these five terms is described in more detail below.

Installed Cost (IC)

The total (turn-key) installed cost of a WTG is made up of the following:

(1) Wind turbine generator and spare parts.

(2) Tower costs.

(3) Installation costs--including labor, foundation costs and site preparation

(4) Transmission, distribution and power conditioning equipment. Includes inverters, circuit breakers, power factor correction equipment, harmonic filtering as well as costs for additional transmission and distribution systems.

(5) Site land costs (if appropriate).

(6) Shipping and transportation costs to the site.

(7) Miscellaneous costs--such as costs for environmental impact statements, engineering fees, etc.

The installed cost for WTG is a sum of all the above-mentioned costs. While some of these costs are application dependent, such as installation costs, shipping costs, land costs, etc., the major costs are items 1-4 where costs associated with the WTG machine strongly dominate. Thus, the IC term usually can be thought of as primarily WTG dependent.

AKWH (Annual Kilowatt-Hours)

The total annual kilowatt hours produced by the WTG system is, of course, dependent on the site wind energy and the WTG design. In general, this term can be expressed as:

$$AKWH = (8760\ P_r\ C_f)\gamma \qquad \text{(B-4.7)}$$

where

P_r = the rated power of the WTG

C_f = the capacity factor of the WTG in a given wind regime

8760 = the number of hours per year

γ = a number less than one that accounts for the time the WTG is shut down when the wind is blowing. This number is usually called WTG availability.

A method for quickly estimating WTG energy output has been developed by Asmussen et. al.* and is breifly outlined below. This method makes use of the following assumptions: (1) that WTG machine characteristics can be approximated by piecewise continuous straight lines between cut-in, rated and cut-out velocities and (2) that sites with mean wind speeds greater than 4.0m/s (8.9 mph), i.e., "economic" WTG sites, tend to have Rayleigh frequency distributions. Under these assumptions the following expression for WTG capacity factor can be derived:

$$C_f = \frac{a\sqrt{2}\pi}{(V_r - V_i)} \left[\text{erf}\left(\frac{V_r}{a}\right) - \text{erf}\left(\frac{V_i}{a}\right)\right] - \exp\left(-1/2\left(\frac{V_o}{a}\right)^2\right) \qquad \text{(B-4.8)}$$

where

V_i = cut-in wind speed
V_r = rated wind speed
V_o = cut-out wind speed
V_m = mean wind speed

$$a = \frac{2}{\pi} V_m$$

The error function in equation (B-4.8) is defined by

$$\text{erf}\, x = \frac{1}{\sqrt{2}\pi} \int_0^x \exp\left(-\frac{y^2}{2}\right) dy \qquad \text{(B-4.9)}$$

Equations (B-4.7) - (B-4.9) clearly indicate that under the above mentioned approximations the energy output and the capacity factor depend only on WTG cut-in, rated, cut-out and site mean wind speed and WTG rated power. Thus, these

*Asmussen, J., D. Manner and G. L. Park, "An Analytical Expression for the Specific Output of Wind Turbine Generators," Proceedings of IEEE, Vol. 66, No. 10, October 1978, pp. 1295-1298.

equations demonstrate that AKWH is strongly mean wind speed and WTG machine dependent. Note that the only site wind characteristic required is the mean wind speed at the height where the WTG cut-in, rated and cut-out wind speeds have been specified. The height usually is hub height or, as with some WTG designs, 9.14 m (30 feet).

CRF (Capital Recovery Factor) and LF (Levelizing Factor)

While the capital recovery factor and the levelizing factor depend on the number of years of WTG life, N, they are primarily dependent on WTG application factors. They depend strongly on interest rates and the escalation of labor costs over the lifetime of the WTG. They vary from one application to another.

AOM (Annual Operation and Maintenance

The annual operation and maintenance costs are strong functions of WTG machine design (reliability and individual WTG component costs) and labor costs; i.e., this factor is both WTG design and application dependent. Ideally a WTG should be designed to minimize these costs. However, a reduction in) and M may result in an increase in WTG initial costs (IC) and thus optimum WTG design becomes a tradeoff between IC and O and M costs to minimize overall WTG system costs. Due to the lack of real (1979) WTG operating experience, WTG O and M costs are very speculative and are expected to vary widely from one WTG design to another. These costs will be high initially in the first years of WTG development and demonstration, but after a number of years of experience it is expected that they will be reduced to minimal levels. In this study it is assumed that WTG O and M will be approximately 1% of IC; i.e., AOM = .01IC. Then equation (B-4.6) can be written as

$$\bar{y} = \frac{IC}{AKWH} (CRF+0.01\ CRFG_1) = \frac{IC}{AKWH}\ CRF(1 + 0.01\ G_1) \qquad \text{(B-4.10)}$$

A solution for y_o and $\bar{y}$ requires that IC, AKWH, CRF, G_1 and G_2 be determined or calculated. Equation (B-4.10) shows the importance of the ratio IC/AKWH in determining WTG economics. This ratio represents the answer to the question of how much energy can a WTG design extract from a given wind regime for how much money. It can be used as a "figure of merit" when comparing different WTG designs.

In many WTG applications electric energy is sold back to the utility at a different price than the WTG owner purchases energy. The last term in equation (B-4.1) then becomes two separate terms, each accounting for the different electric energy prices and the fractions of the total WTG output energy consumed by the WTG user and sold back to the utility. Assuming that utility purchased energy is a constant fraction, $1/\alpha$, of the utility electric prices over the WTG system lifetime the last term in equation (B-4.1), (expressed in terms of present electric energy cost y_o) becomes

$$\frac{1 + \left(\frac{1+r_1}{1+r_3}\right)^N}{1 - \left(\frac{1+r_1}{1+r_3}\right)} (1+r_3)^N (AKWH) y_o \left((1-\beta) + \frac{\beta}{\alpha}\right) \qquad \text{(B-4.11)}$$

where

β = the fraction of the total WTG electrical output sold to the utility

$\frac{1}{\alpha}$ = the ratio of utility purchase price and the price of electric energy for the WTG owner

Appendix C

C.1 Thermal heat loss calculation

C.2 Description of minicomputer test programs

C.3 Sensors required for Trombe wall

C.4 Sensors required for utility interface/load consumption

Appendix C.1

Thermal Heat Loss Calculation

The following relations and technical development is based on the ASHRAE established procedures. The procedure depends on categorizing all surfaces by material and area, itemizing the thermal resistance of each surface, and utilizing the degree heating days to evaluate the heat loss resulting from the given surface. It is assumed that the above ground degree heating days is 6900 (ASHRAE established value for Lansing) while for underground the degree heating days is conservatively estimated at 2500. It should be noted that with the federal standards requiring reduced interior temperatures both of the above values will be decreased, particularly the underground degree heating values.

The appropriate equations for heat loss calculation are given by:

$$\text{BTU} = (\text{degree heating days}) \times (24) \times \left(\frac{\text{Area}}{R_T}\right)$$

where

$$\frac{\text{Area}}{R_T} = \sum_{\text{all}} (A/RT)$$

RT is the thermal impedance determined from look-up tables for different materials and thicknesses of materials.

Appendix C.2

Minicomputer Test Programs

This appendix contains the description of the minicomputer check out programs: IOTEST, ASCII1 and FLOP1.

IOTEST

IOTEST is a routine that echoes a line of input back to the teletype. Characters are read into a buffer in the NEXTIN loop until a carriage return (ASCII 15_8) is found. Then the characters are echoed from the same buffer in the NEXTOT loop. A new line is prompted when a carriage return is encountered. If a "bell" (control-G) is found first the

NORTH BUILDING

Wall	Area	R	Area / R
Free Air (exterior wall)	1296.	1.49	869.80
Glass	37.	1.54	24.03
Still Air (interiow wall air lock)	294.	2.00	147.00
Doors	67.	2.33	28.76
Ceiling			
Free air	2232.	7.24	308.29
Floor			
	2232	15.00*	148.8

*Thermal contact to surfaces experiencing 2500 D.D.

SOUTH BUILDING

Wall	Area	R	Area/R
Free Air (exterior wall)	560	1.49	375.84
Still Air (interior wall)	240	2.00	120.00
Doors	40	2.33	16.17
Ceiling			
Free Air	1245	7.24	171.96
Skylight	102	1.43	71.33
Basement			
Wall	1154	16.32	70.71
Floor	1244	15.00*	82.93

WEST BUILDING

Wall	Area	R	A/R
Free Air	693	1.49	465.1
Still Air	152	2.00	76.0
Doors	40	2.33	17.18
Ceiling			
	719	7.24	99.31
Floor			
	719	15.00*	47.93

HEAT LOSS CALCULATIONS FOR PRELIMINARY BUILDING DESIGN

CASE 1: Dirt cover as shown on preliminary design
(Assumed R_T = 15.0 for dirt.)
1" polystyrene on ceiling.

CASE 2: No dirt
1" polystyrene on ceiling

CASE 3: No dirt
w/wall insulation: 1" polystyrene
$3\frac{1}{2}$" fiberglass
and ceiling insulation 12" fiberglass

CASE 4: Same as Case 3 w/dirt cover shown on preliminary design.

NORTH BUILDING

SURFACE	AREA (sq.ft.)	CASE 1 R_T	CASE 1 Loss 10^6BTUs	CASE 2 R_T	CASE 2 Loss	CASE 3 R_T	CASE 3 Loss	CASE 4 R_T	CASE 4 Loss
CEILING	2232.	22.07	16.75	7.68	48.13	38.0	9.73	52.4	7.05
WALLS									
Dirt Covered	894.	16.32*	3.29	1.49	99.36	8.4	17.64	23.23	6.37
Free Air	402.	1.49	44.68	1.49	44.68	8.4	7.93	8.4	7.93
Still Air	294.	2.00	24.34	2.00	24.34	8.91	5.46	8.91	5.46
Glass	37.	1.54	3.98	1.54	3.98	1.54	3.98	1.54	3.98
Doors	67.	2.33	4.76	2.33	4.76	2.33	4.76	2.33	4.76
							39.75		28.5
FLOOR	2232.	15.0*	8.928	15.0*	8.928	15.0*	8.93	15.0*	8.93
TOTAL			106.7		234.18		58.41		44.48

SOUTH BUILDING

SURFACE	AREA (sq.ft.)	CASE 1 R_T	CASE 1 Loss 10^6BTUs	CASE 2 R_T	CASE 2 Loss	CASE 3 R_T	CASE 3 Loss	CASE 4 R_T	CASE 4 Loss
CEILING									
Dirt Covered	803.	22.07	6.03	7.68	17.31	38.0	3.50	52.4	2.54
Free Air	442.	7.68	9.53	7.68	9.53	38.0	1.93	38.0	1.93
Sky Light	102.	1.43	11.81	1.43	11.81	1.43	11.81	1.43	11.81
			27.37		38.65		17.24		16.28
WALLS									
Dirt Covered	272.	16.32*	1.00	1.49	30.23	8.4	5.36	23.23	1.94
Free Air	288.	1.49	32.01	1.49	32.01	8.4	5.68	8.4	5.68
Still Air	240.	2.00	19.87	2.00	19.87	8.91	4.46	8.91	4.46
Doors	40.	2.33	17.17	2.33	17.17	2.33	2.84	2.33	2.84
BASEMENT WALLS									
Dirt Cover	1154.	16.32*	4.24	16.32*	4.24	16.32*	4.24	16.32*	4.24
BASEMENT FLOOR	1244	15.0	4.98	15.0*	4.98	15.0*	4.98	15.0*	4.98
TOTAL			92.31		147.15		44.8		40.04

WEST BUILDING

SURFACE	AREA (sq.ft.)	CASE 1 R_T	CASE 1 Loss 10^6BTUs	CASE 2 R_T	CASE 2 Loss	CASE 3 R_T	CASE 3 Loss	CASE 4 R_T	CASE 4 Loss
CEILING	719.	22.07	5.39	7.68	15.50	38.0	3.13	52.4	2.27
WALLS									
Dirt Covered	272.	16.32*	1.00	1.49	30.23	8.4	5.36	23.23	1.94
Free Air	420.5	1.49	46.73	1.49	46.73	8.4	8.89	8.4	8.29
Still Air	152.	2.00	12.59	2.00	12.59	8.91	2.83	8.91	2.83
Doors	40.	2.33	2.84	2.33	2.84	2.33	2.84	2.33	2.84
			63.16						15.9
FLOOR	7.9.	15.0*	2.876	15.0*	2.876	15.0*	2.876	15.0*	2.876
TOTAL			71.43		110.77		25.93		21.0
SITE TOTAL			$270x10^6$		$490x.0^6$		$130x10^6$		$105x10^6$

program exits to the system monitor.

Because carriage return and not line feed (ASCII 12_8) is used as an end-of-line mark, the line feed is output at the beginning of the second and subsequent lines.

ASCII1

ASCII1 is a straightforward program that inputs two base 10 numbers and outputs their sum, also in base 10. To do this, ASCII1 must perform the ASCII to binary conversion on input and binary to ASCII conversion on output. Program execution begins at START with a header and some instructions printed at the teletype, followed by the "ADD?" prompt. When the teletype input is available to the program it is tested. If the first character is a number the ASCIN subroutine is called. If the first three characters are "END" the program terminates. All other input is discarded and the prompt is reissued.

The call to ASCIN is made with the destination address in R5 and with the R5 as the return register. ASCIN assumes the first ASCII digit is already in R0 and consequently jumps into the middle of its loop. Each subsequent character is checked to see if it is a number and the subroutine returns when a non-number is found. For each valid digit, the previous running total is multiplied by 10 and the current digit added minus the ASCII zero offset. When the subroutine is completed the result is stored in the proper location. (The address in R5 was pushed onto the stack with the subroutine call.)

After the first number is decoded into NUM1, the first digit of the second number is searched for with the GETN2 loop. Then it too is decoded by ASCIN and stored at NUM2. The two numbers are then added and their sum is output. This requires a call to the ASCOUT subroutine.

The ASCOUT call is made with R5 as the return register and is followed by two words of data. The first is the address of the output buffer and the second is the address of the data. Since ASCOUT uses two registers (R1 and R2), they are saved upon entering the routine and restored before returning. ASCOUT then uses the ASCDIG macro for each of the four most significant digits. This macro produces code which subtracts the given number (.NUM) as many times as possible with a positive result. The subtraction count is converted to an ASCII digit and stored at the proper location in the buffer. After this has been done through the tens digit, the units digit remains in the data word. This final digit is converted to ASCII and stored, the registers are restored, and the proper return is set up and executed.

In the main routine, the sum in output and the program loops back to issue another prompt.

FLOP1

FLOP1 is a fairly sophisticated program which contains several macros--most for string searching. These are:

.STRNG1 is a macro that compares the ASCII character in R0 to a given character (.CHAR), branching to .NEQADD if not equal.

.STRGCK is a macro that compares two ASCII strings, presumably in input string against a command string. To use this macro the two input strings must be in memory at addresses .STR1AD and .STR2AD. A character count (.NUMC) and an address (.NEQADD) for the branch on non-equality must also be supplied.

.STRGIN is a macro which inputs characters in a certain ASCII range (.LOC - .HIC) into a buffer at .BUFPNT. If the characters are digits, an .OFFSET can be subtracted off first.

.GETCHR is a macro which can be used to search a string for a character range. .GETCHR was not used in this program. Instead .GETC2 is used to input characters through the first occurence of one in the range (.LOC - .HIC). If a line feed (end-of-line) is detected first a branch is made to .NOTHERE.

Macro .ENDLIN is used to discard the remaining portion of an input line. It inputs characters through a line feed.

The last macro, .WAITER, is not a string operator, but is used to wait in a loop until masked bits in .ADDR are non-zero. (The contents of .ADDR are ended with .MASK.)

Program execution begins at START. A header is printed as is a prompt asking for a floppy track number ($0-76_{10}$). The input string "END" will terminate the program and is the only other acceptable input. Everything else is discarded. The ASCIN subroutine, described in the ASCII1 routine of this appendix is used to decode the track number. If it is valid, the floppy read subroutine (FLOPRD) is called. An invalid track number is ignored and a new track number requested.

In the FLOPRD routine, the desired track and sector are located and a read performed. (The sector number starts at 1 and is incremented each time the subroutine is called.) After the read, the contents of the floppy status and data registers are output. The display subroutine DSPLWD does not work properly, so ODT was used in the actual testing process to display these registers. The subroutine then returns to the main program which asks to reposition the floppy (try another track) or for a command (which will terminate the program).

Appendix C. 3

SENSORS FOR TROMBE WALL

SENSOR #	Name & Part Number	Output	Quantity Measured	Interface #	Interface Cost	Sensor Cost	Total Cost
S32	AD 590 KH Temperature Transover	$1\mu A/^{o}K$	Outside ambient temp. near Trombe	2-23	22.50	6.00	22.50
S33	AD 590 KH		Temp. inside solar collector	2-33	22.50	6.00	22.50
S34	AD 590 KH		Phase-change material temp.	2-34	22.50	6.00	22.50
S35	AD 590 KH		Inside room ambient temp.	2-35	22.50	6.00	22.50
S36	Eppley Model 8-48	$11\mu V/Wm^{-2}$	Total Solar Radiation incident on Trombe	1-36	19.25	590.00	609.25

Appendix C.4

SENSORS FOR UTILITY INTERFACE/LOAD CONSUMPTION

SENSOR #	SENSOR Name & Part Number	Output	Quantity Measured	Interface #	Interface Cost	Sensor Cost	Total Cost
S24	OSI PC5-98C 3ϕ, 240 V_{AC}, 400 KW Power Transducer	0-10 V_{DC}	Power supplied by Utility	(C)	66.00	261.80	
S25	OSI Pc5-71C 3ϕ, 240 V_{AC}, 80KW Power Transducer	0-10 V_{DC}	Excess Power supplied to utility	(C)	66.00	261.80	
S26	OSI PC5- C 3ϕ, 240 V_{AC}, Power Transducer	0-10 V_{DC}	Power consumed by Load 1	(C)	66.00		
S27	OSI PC5- C , 240 V_{AC}, Power Transducer	0-1- V_{DC}	Power consumed by Load 2	(C)	66.00		
S28	OSI PC5- C Power Transducer	0-10 V_{DC}	Power consumed by Load 3	(C)	66.00		
S29	OSI PC5- C Power Transducer	0-10 V_{DC}	Power consumed by Load 4	(C)	66.00		