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SYSTEM DESIGN, TEST RESULTS, AND ECONOMIC ANALYSIS OF A FLYWHEEL ENERGY STORAGE AND CONVERSION SYSTEM FOR PHOTOVOLTAIC APPLICATIONS*+‡‡

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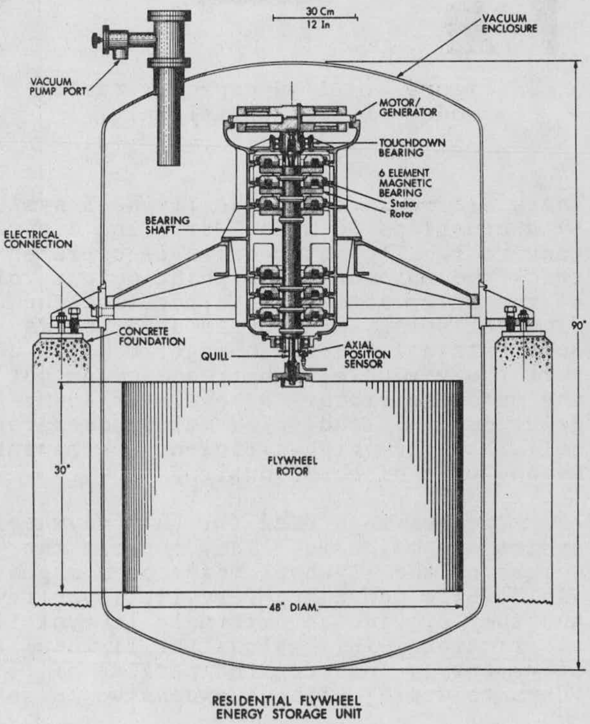
ABSTRACT

MIT Lincoln Laboratory is developing a flywheel interface and storage system for use with photovoltaic power sources. Test data on the performance of components built to investigate the feasibility of such a system, and the results of economic studies of the system showing user-worth analysis and manufacturing-cost estimates, are presented. The system has magnetic bearings, a maximum-power-point tracker, DC input, and cycloconverter output from an ironless-armature motor-generator.

INTRODUCTION

Solar photovoltaic (PV) power systems requiring on-site storage presently use electric storage batteries. Those requiring regulated AC-output power use solid-state inverters for power conditioning. Studies of future PV power systems generally assume continued use of such elements because of the generally held conviction that no other system can compete economically with batteries and inverters. However, studies performed at MIT Lincoln Laboratory (MIT LL) indicate that flywheel energy storage with integrated power-conditioning electronics can be technically and economically competitive with either present-day or advanced batteries. This conclusion requires that the flywheel be properly configured and that both approaches be analyzed in a total system context.

During the past year, a residential and a 100-kW load-center flywheel system have been designed. The residential unit is shown in Figure 1. A 1/10 capacity scale model of the unit has been built by MIT LL, as shown in Figure 2, and is now being tested to verify system performance. A user-worth analysis of the flywheel system has been performed by the MIT Energy Laboratory to determine how much a prospective buyer might be willing to pay for it. Three contracts for production-cost analysis of the flywheel system will be completed by March 1980. Advanced low-cost prototype rotors are being purchased for retrofit into the subscale system for further testing.



RESIDENTIAL FLYWHEEL ENERGY STORAGE UNIT

Figure 1

The important new elements of the system are the power conditioning and bearings. A battery system uses an inverter to produce regulated AC power from a DC battery. Also, power electronics are often used to match the PV array voltage to the battery or to control battery charging.

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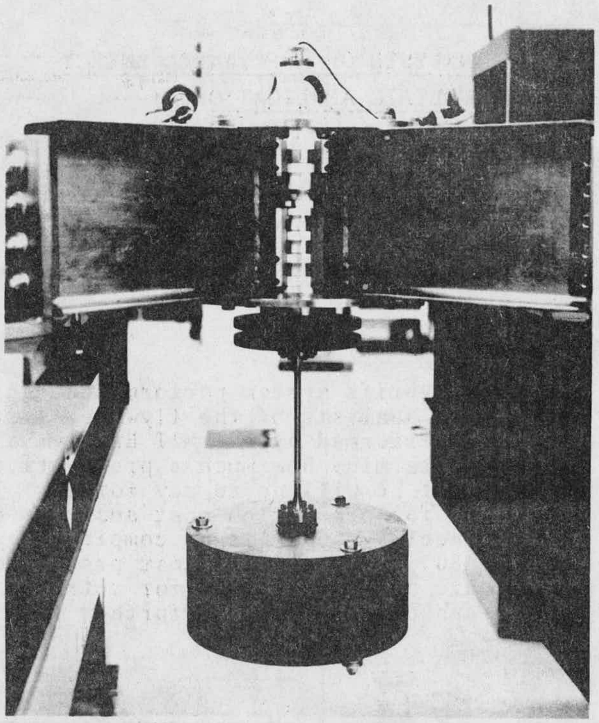


Figure 2. 1/10 capacity scale model of residential unit.

These are replaced in the flywheel system by a brushless DC-motor drive and a cycloconverter. The motor drive is operated to track the maximum-power-point output voltage of the solar array and to regulate the flywheel speed. The cycloconverter is a solid-state frequency changer used to convert the variable high-frequency output of the motor-generator to regulated 60-Hz AC power for the load. The motor-generator itself is a very high-efficiency permanent magnet unit of novel design.

The bearings used for this flywheel system are magnetic. They support the weight of the flywheel rotor on a magnetic field while consuming very little energy and they provide an extremely low rotational friction. This allows the flywheel to store energy for required periods of time (days to weeks) without excessive losses.

The following sections summarize the results of component testing of the subscale system to date (December 1979), and include the results of user-worth studies to date for stand-alone and utility-interactive PV flywheel systems. System testing is not yet complete.

COMPONENT TESTING

The flywheel system consists of the following major elements:

Rotor
Bearings
Shafts
Motor generator
Motor-drive electronics
Cycloconverter electronics
Vacuum system

The rotating mechanical elements of the subscale system are drawn in a design layout in Figure 3. This design differs from the residential unit primarily in the lack of production cost considerations, in the sizes, and in the extra separation between components for ease of testing. System dynamics and component function are deliberately kept similar. A summary of the scaling relations between prototype, residential, and 100-kW size units is given for overall system parameters in Table 1. The resulting component scaling is given in Table 2. The present flywheel rotor is a series of seven steel rings pressed onto a steel hub, to allow testing of the system concept before introducing the uncertainties of an advanced rotor design. The vacuum system is a modification of an existing test chamber to allow above-ground testing, and is not representative of the intended below-grade residential system concept which is shown in Figure 4. The components tested for performance are the magnetic bearings, motor generator, shaft dynamics, and electronics.

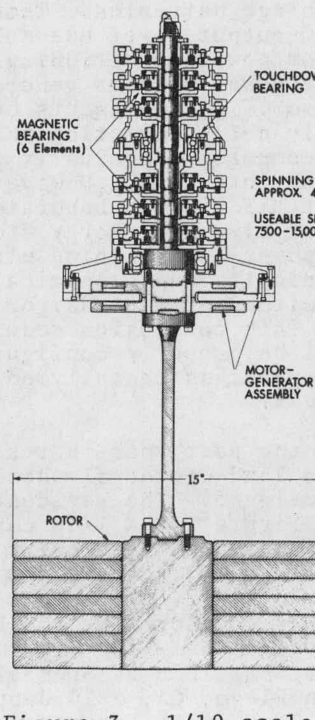
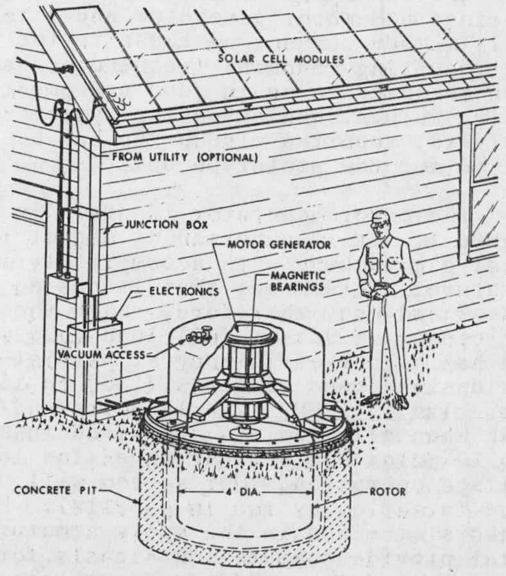


Figure 3. 1/10 scale model layout.



RESIDENTIAL PHOTOVOLTAIC FLYWHEEL SYSTEM

Figure 4

TABLE 1
FLYWHEEL SYSTEM PARAMETERS

PARAMETERS	UNIT	SUBSCALE	40 KWH RESIDENCE	500-KWH LOAD CENTER
ENERGY STORED	KWH	1 TO 4	40	500
ENERGY AVAILABLE	KWH	.6 TO 2.5	25	325
POWER INPUT	KW	0.50	8	100
POWER OUTPUT				
STEADY STATE	KW	0.50	8	100
PEAK	KW	.625	10	100
INPUT D.C. VOLTAGE MAX.	VOLTS DC	400	400	800
INPUT S.C. CURRENT MAX.	AMPS DC	2.5	40	260
INPUT VOLTAGE RANGE	VOLTS DC	220-330	220-330	440-660
INPUT CURRENT MAX.	AMPS DC	2.3	35	230
OUTPUT VOLTAGE	RMS VOLTS DC	110	220 C.T.	440
MAX. OUTPUT CURRENT	RMS AMPS PER PHASE	5.6	45	130
PHASES	NO.	1	1	3

TABLE 2
COMPONENT POINT DESIGNS, 1980

	PROTOTYPE	RESIDENCE	LOAD CENTER
ROTOR			
WEIGHT, LB.	400	4000	500,000
DIAMETER, IN.	20	48	112
LENGTH, IN.	20	32	70
MAX. SPEED, KRPM	15	10	6.5
MOTOR/GENERATOR			
PEAK POWER, KW	.625	10	100
AVG. POWER, KW	.500	8	100
DIAMETER, IN.	8	16	34
TOTAL MAGNET VOLUME, $IN.^3$	4	60	720
MAGNET WEIGHT, LBS.	2.2	17.4	216
MAGNETIC BEARING -6 PER SYSTEM			
DIAMETER, IN.	3.2	9	32
GAP, MILS	18	30	57
NOMINAL AMP -TURNS OPERATING	850	1400	2700
NOMINAL DISSIPATION - WATTS PER BEARING			
PERM. MAGNET DESIGN	.65	.65	.65
ELECTROMAGNET DESIGN	50	50	50
50/50 DESIGN	12	12	12
PM DESIGN MAGNET VOLUME, $IN.^3$	.43	5.8	136
PM DESIGN TOTAL FOR ALL 6 BEARINGS MAGNET WEIGHT, LBS.	.72	9.6	228
ELECTRONICS			
CROSSOVER FREQUENCY W_C HZ	30	23	16
MAX. SWITCHING FREQ. KHZ	1.25	1.25	.54

The magnetic bearing supports the 400-lb. rotating weight of the flywheel with a power dissipation of 4.0 watts. This bearing is a radially passive, axially active permanent magnet design. It uses $SmCo_5$ magnets to minimize size and weight and thus minimize total bearing cost. The bearing assembly is shown in Figure 5. A modified design for lower cost is drawn in Figure 6, requiring minimal machining operations on cast magnets. Bearing drag has not yet been measured at full speed, but is expected to be less than 0.1% energy dissipation per hour (1.8×10^6 N-m/rad/sec). Bearing power requirements, including position servo, can be drawn from the flywheel via the motor-generator windings or from the solar array and are designed to run on a small battery through power outages of many hours' duration. Touchdown ball bearings act as a catcher if magnetic levitation is removed. The magnetic bearing stiffness in the axial direction is -31,500 lbs/inch (-5.6×10^6 N-m). The radial displacement stiffness is 4,500 lbs-inch (8.0×10^5 N-m). Gimballing torque stiffness is approximately 6,400 inch-lbs per radian (71 N-m per radian). Clearances to the touchdown bearings are 30-mils stop-to-stop radially and 14-mils stop-to-stop axially. The quill shaft allows additional motion of the rotor relative to the bearing shaft to allow the rotor to be more self-aligning if imperfectly balanced.

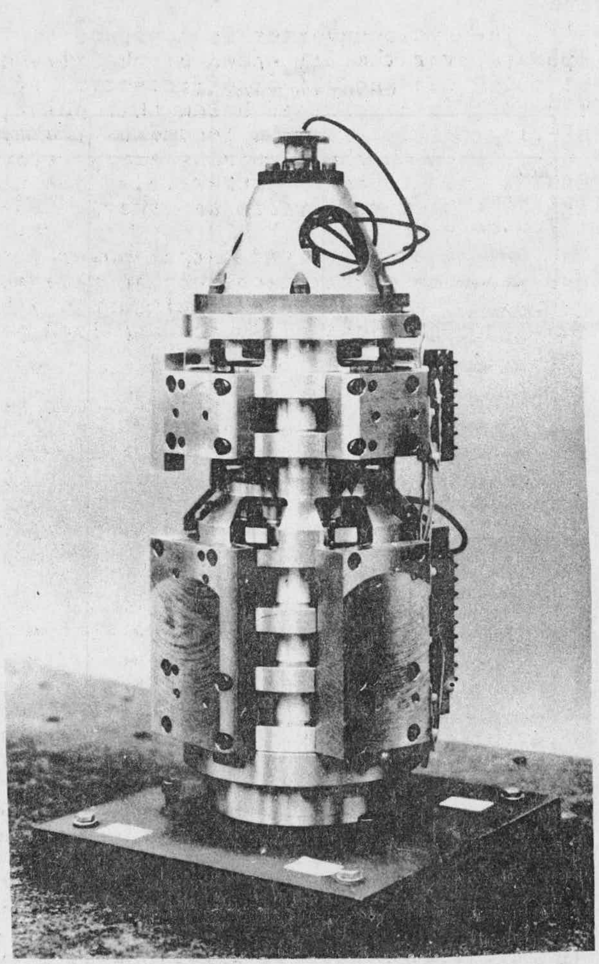


Figure 5. Bearing assembly.

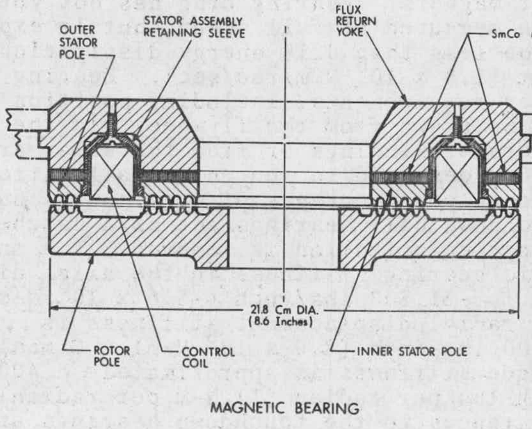


Figure 6. Bearing redesign.

The shaft is designed in two sections, with a stiff upper portion connecting the bearings and motor generator and a thin quill member connecting these to the rotor. The resulting resonant frequencies have been measured to be in good agreement with design values. An extensive system stability analysis, reported elsewhere, has been completed for the prototype unit.

The motor generator is drawn in Figure 7. It is a permanent magnet 10-pole axial-gap machine with a completely ironless armature. This means that it has no iron losses and can, therefore, reach the design efficiency of 96% at full load (625 watts) and has higher efficiency at partial loads. Its design speed range is 7,500 to 15,000 rpm. Its back EMF is 0.18 volts/rad/sec peak when all windings are wired in series. The 10 poles can be rearranged for lower voltage operation. Our system will use five in series by two in parallel. Hall sensors embedded in the epoxy armature material provide commutation signals for the electronic drive. Eddy current losses in the Litz-wire armature windings are under one watt at full speed. The armature is conduction-cooled by use of Litz-wire braid strips leading the heat out to the mounting surfaces, aided by a thermally conductive loaded epoxy, to keep average operating temperature below 40°C. Coil resistance, the main source of loss, is 0.045 ohms per pole per phase, with three phases of windings Y-connected.

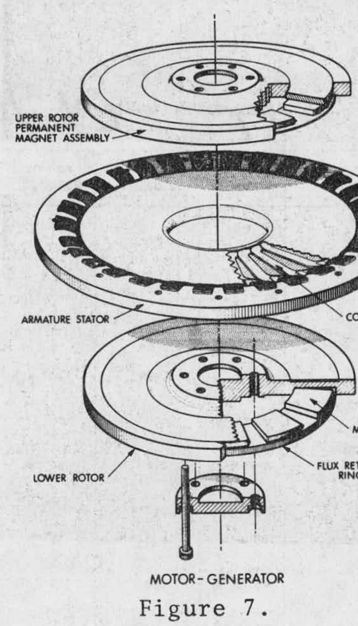
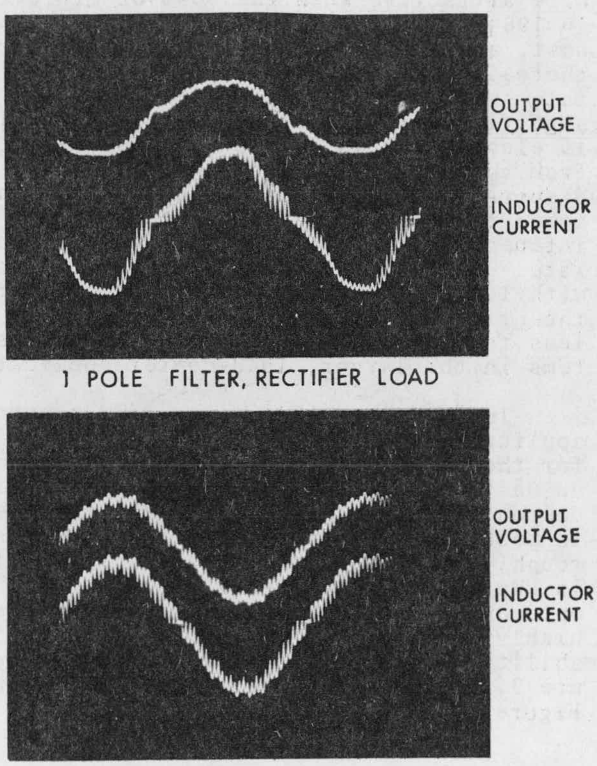


Figure 7.

The rotor is a high-stress design, with a titanium web in the prototype model holding the $SmCo_5$ magnets in pure compression. The magnets see no more than 6 KSI and show no signs of cracking at these stress levels.

The motoring electronics can be broken down into a DC-DC downconverter, running at 20 KHz with an efficiency of 98% at full load, and a three-phase motor drive running at electrical frequencies of 625 to 1250 Hz with an efficiency of 96% at full load. The three-phase drive was built using gate turn-off silicon control rectifiers (SCR's) to allow testing of both force-commutated and load-commutated operation. Normally, the system operates load-commutated so that larger systems are not restricted by this device selection.

The output electronics consist of a cycloconverter and a small LC filter to eliminate the 3670- to 7340-Hz components from the 60-Hz output waveform. The cycloconverter consists of a group of electronic switches which connect one of the three M/G phases to each side of the output transformer to approximate the desired output voltage. The control circuit used is the cosine-wave type with high built-in immunity to electrical noise. The output waveform is shown in Figure 8.



1 POLE FILTER, RECTIFIER LOAD

PARTIAL FILTER, RESISTIVE LOAD

CYCLOCONVERTER
60-Hz WAVEFORM, WORST CASE

Figure 8.

The cycloconverter is designed to operate over the 2:1 speed of the flywheel at full load and 94% of efficiency. If the flywheel is discharged below this point, a relay disconnects the load from the cycloconverter, and the remaining energy store can be used to power housekeeping functions in the system or perform an orderly shut-down.

Flywheel input and output power functions use separate electronics but the same motor generator. This allows simultaneous arbitrary combinations of source and load power with a minimum total cost.

The total system performance can be summarized in terms of the energy efficiency from solar array input to AC output over a typical daily cycle with a residential load. The resulting cycle efficiency is predicted to be 70%. Battery and inverter systems normally do no better than this, and advanced batteries may not do as well.

FLYWHEEL ECONOMICS

Initial estimates of flywheel system costs are shown in Table 3 for 1979 technology low-cost scenario. These include the entire power conditioning and storage system installed at the (residential) site, but do not include the solar array. These are the high, medium, and low cost assumptions used for comparison with the user-worth analysis to date. More precise cost estimates by prospective manufacturers are now being completed.

TABLE 3
RESIDENTIAL FLYWHEEL SYSTEM COST ESTIMATES
1980 DOLLARS

	"HIGH" 1979 TECHNOLOGY	"MEDIUM" 1985 HIGH ESTIMATE	"LOW" 1985 LOW ESTIMATE
STORAGE CAPACITY $/KWH	$ 328	$ 168	$ 98
INPUT $/KWDC	$ 140	$ 105	$ 42
OUTPUT $/KWAC	$ 302	$ 208	$ 147
20 KWH TOTAL	$10,700	$ 7,000	$3,726
40 KWH TOTAL	$17,314	$10,360	$5,621

A worth analysis was conducted by the MIT Energy Laboratory to assess economic viability for the advanced flywheel concept as supplemental storage to photovoltaic energy conversion systems. Two applications were studied: a single-family residence utilizing an 8-kWp PV array and a multi-family load center requiring an array on the order of 100 kWp. The objectives were to determine optimal flywheel sizing for the various operating environments and to make a determination of the sensitive financial parameters which would effect market penetration. The operating modes included both utility-interface and remote, stand-alone operation. The following remarks apply to the residence application unless the load center is explicitly noted.

Both applications were modeled for the geographic regions centered around Phoenix and Boston. Phoenix runs revealed break-even capital cost figures at least twice as high as those for Boston when all parameters other than insolation data are held fixed. Break-even capital cost was examined here, both in system and flywheel component terms. By standard definition, it is defined to be:

$$BECC = \sum_{i=1}^{life} \frac{BENEFITS-COSTS}{(1+R)^{i}}$$

where:

BENEFITS = total dollar equivalent of utility electricity displaced by the PV-flywheel system; plus, for stand-alone applications, distribution-line costs otherwise incurred.

COSTS = All costs of the system not to be included in the BECC figure (see below).

LIFE = Assumed lifetime of the system: 20 years.

r = discount rate.

In calculating System Break-even Capital Cost, the COSTS figure includes none of the costs associated with any component of the system. It thereby defines the total benefits which accrue to the system over its run life. Hence, what the system BECC must account for are all costs associated with (1) the flywheel storage unit, (2) the PV modules, and (3) all balance-of-system. This includes all maintenance over the life of the system.

The Flywheel Break-even Capital Cost maintains the original definition for BENEFITS, but defines COSTS as the balance-of-PV-system costs plus PV modules priced at an assumed module cost.

The results showed that for a residence in Phoenix with a flat-rate price structure and 0% buyback from the utility, system BECC is \$5,000 with an 80-m^2 array and no flywheel. For the same size array, this figure increases to \$11,500 and \$15,000 for flywheels of 20-kWh and 40-kWh capacity, respectively. Flywheel BECC under the same conditions is a function of assumed balance-of-system costs and PV module costs. For PV modules at the 1985 cost goals of \$.70 Wp (1980\$), and with high BOS costs and 20-kWh capacity assumed, flywheel BECC is \$180/kWh. The latter figure is \$300/kWh when low BOS costs are assumed. Note that these worth values are above the preliminary 1985 high and low cost estimates.

In general, the addition of storage serves to increase the optimum capacity of PV installed when hardware costs are assumed low enough to yield a positive return on investment. When storage is dedicated to the PV array alone, it is shown to have the greatest value when purchase rates by the utility for excess PV-generated electricity are low. This is true since marginal benefits to a fixed-storage capacity decline as buyback rates are increased. However, and again at low-hardware-cost assumptions, the marginal increase in benefits due to a fixed-PV array exceed the marginal decrease in benefits to storage as buyback rates increase, with the net effect of increasing overall system worth. Depending on flywheel and other BOS cost assumptions, at some utility buyback rate below 50%, the addition of storage capacity effects an increase in investment net benefits.

Using the most reasonable set of cost and financing projections for 1985, a PV-flywheel system will begin to look economically attractive when the cost of electricity, in 1980 dollars, exceeds 9¢/kWh (start cost, assuming 3%/year real escalation thereafter). Variations in time-of-day rate setting by the utilities are only significant in affecting storage economics if electricity is bought and sold directly from the storage device, thus acting in a dispersed-system storage mode. It was also found that the most important parameter in influencing system worth was the discount rate. In fact, higher discount rates coupled with longer construction period lags were the primary factors in providing a much less favorable outlook for PV-flywheel systems in the larger, load-center applications.

In the stand-alone (non-grid-connected) applications, optimum configuration sizing for the PV and flywheel with no diesel back-up was found quite insensitive to relative component costs. Flywheel capacity rated in peak-kWh-storage figures is optimum at roughly 2.5-4.0 times the array size rated in kWp. Without a diesel back-up, the optimum size of a flywheel and PV system is highly sensitive to desired service reliability. These results are shown in Figure 9, based on the assumptions shown in Figure 10.

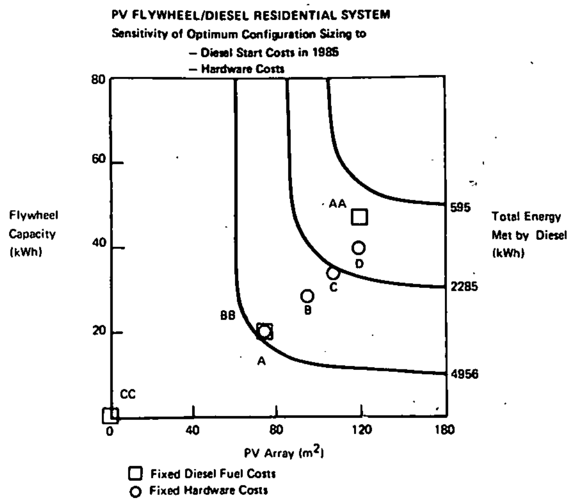


Figure 9.

ASSUMPTIONS

Utility Tie in Costs as Benefits	Diesel Fuel Costs Fixed at $ .07/kWh in 1985; Hardware Costs Varied		Hardware Costs Fixed at PV = $.07/pk Watt FW = Middle; Diesel Fuel Costs in 1986	
• $ .066/kWh 3%/Year Real Price Escalator	AA	PV = .28 FW = Low	A	$ .07/kWh
			B	.097
	BB	PV = .70 FW = Medium	C	.133
• 30 Miles from Grid $8712/Mile			D	.169
	CC	PV = .91 FW = High		After 1986 Escalate at 6.6%/Annum

Figure 10.

With a diesel generator as back-up, and again with no utility connection, there is a high sensitivity of optimum sizing of the tri-component system over the range of hardware and fuel cost projections. For such a system, positive net benefits accrue at just over one mile from the distribution grid when foregoing utility-connect charges are taken as a benefit. Positive net benefits accrue beginning at five miles for the load-center application.

The analysis concludes that flywheel systems are more attractive in residential applications, primarily as a result of differences in construction lags and financing parameters, particularly the discount rate. Issues of component sizing will be highly affected by these parameters as well as by relative PV and flywheel component costs and the market price of alternatives.

CONCLUSIONS

Results to date indicate that a flywheel energy storage and conversion system which competes favorably with storage batteries and inverters in both performance and cost can be built. If actual manufacturing costs are close to 1985 estimated cost values, the worth of the system is greater than the cost for residential stand-alone applications and for a number of utility-interactive residential applications with 50% or less buyback rates. Where solar PV energy storage is feasible, flywheel systems are of interest.