RESIDENTIAL PHOTOVOLTAIC FLYWHEEL STORAGE SYSTEM PERFORMANCE AND COST * ** +

DOE/ET/20279-92

CONF-800806--22

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Abstract

A subscale prototype of a flywheel energy storage and conversion system for use with photovoltaic power systems of residential and intermediate load-center size has been designed, built and tested by MIT Lincoln Laboratory. System design, including details of such key components as magnetic bearings, motor generator, and power-conditioning electronics, are described. Performance results of prototype testing are given and indicate that this system is the equal of or superior to battery and inverter systems for the same application. Results of cost and user-worth analysis show that residential systems are economically feasible in stand-alone and in utility-interactive applications.

Introduction

This report describes the MIT Lincoln Laboratory development program for inertial energy storage systems to be used with residential photovoltaic installations. Inertial energy storage will compete with batteries which are now the only practical electrical energy storage component available. Desirable characteristics of any energy storage system are: low standby losses, high operating efficiency, and high energy density. The development of magnetic bearings and high-performance flywheel rotors makes possible economically attractive energy storage systems which can meet these requirements. The input and output electronics are integrated with the motor/generator for maximum performance and reliability at minimum cost.

The design and testing of a laboratory 1/10-scale, 1-4 kWh flywheel system are described, as are the preliminary design of a residential 40-kWh-peak energy storage system and the results of industrial cost studies of the residential unit. A larger 500-kWh-peak energy-storage load center has been costed using scaling laws and input data derived from the smaller units. A summary of user-worth studies is presented which relates the amount of energy stored to the area of PV collector in terms of a net cost benefit to the potential buyer.

The specifications for the three inertial energy storage systems are shown in Table I.

PARAMETERS	UNIT	SUBSCALE	40-kWh RESIDENCE	500-kWh LOAD CENTER
ENERGY STORED	kWh	1 TO 4	40	500
ROTOR WEIGHT	lbs	350	2,700	33,000
ENERGY AVAILABLE	kWh	0.6 TO 2.5	25	325
MAXIMUM SPEED	krpm	15	12	6.5
POWER INPUT	kW	0.50	8	100
POWER OUTPUT				
STEADY STATE	kW	0.50	8	100
PEAK	kW	0.625	10	100
INPUT O.C. VOLTAGE MAXIMUM	VOLTS DC	400	400	800
INPUT S.C. CURRENT MAXIMUM	AMPS DC	2.5	40	260
INPUT VOLTAGE RANGE	VOLTS DC	220-330	220-330	440-660
INPUT CURRENT MAXIMUM	AMPS DC	2.3	35	230
OUTPUT VOLTAGE	RMS VOLTS DC	110	200 C.T.	440
MAXIMUM OUTPUT CURRENT	RMS AMPS PER PHASE	5.6	45	130
PHASES	NO.	1	1	3

Table I
Flywheel System Parameters

Description of 1/10-Scale Laboratory System

The features and characteristics of this assembly have been previously described (1), (2), but a brief review is given for clarity. Figure 1 is a section through the magnetic bearing and shaft assembly without the external supports. The principal components are:

Flywheel Rotor
Motor/Generator
Six Magnetic Bearings
Shaft
Quill.

The ball bearings are used to support the shaft only if the magnetic levitation is removed, otherwise there is no contact. The quill allows the flywheel to be self-aligning if not perfectly balanced. The present flywheel is made from steel discs pressed onto a hub. One or more advanced-design flywheel rotors of low cost are being procured and will be substituted for the steel rotor to test a configuration typical of a residential energy storage system.

Figure 2 shows the complete assembly ready to be placed in the vacuum tank. A thick steel enclosure surrounds the flywheel for containment in the unlikely event of a quill or flywheel failure. All large components were spin tested to 10% over the 15,000-RPM maximum operating speed.

Figure 3 is a block diagram of the electronic systems. DC from the array is switched by the motor SCR drive into the 3-phase "Y"-connected armature windings. Hall generators provide motor phase signals for unidirectional rotation at starting. The output cycloconverter is fed directly from the common motor-generator armature terminals. Power can flow directly from the motor bridge to the output or be put into or withdrawn from the flywheel through the armature coils. The cycloconverter transforms the variable voltage and frequency: 3-phase motor AC to single-phase, 60 Hz, 117 V. Power flow

*This work was sponsored by the U. S. Department of Energy.

**The U. S. Government assumes no responsibility for the work presented.

+Presented at the 15th Intersociety Energy Conversion Engineering Conference, Seattle, WA, August 18-22, 1980.

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DISCLAIMER

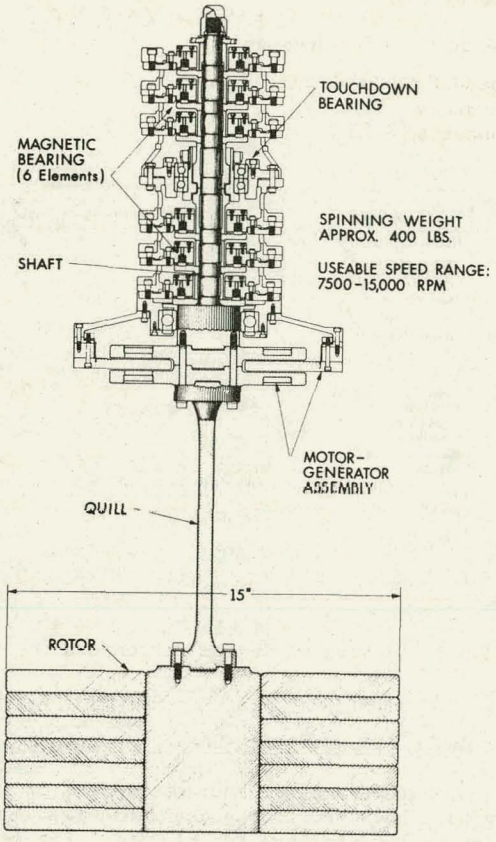

Figure 1
1/10-scale experimental flywheel.

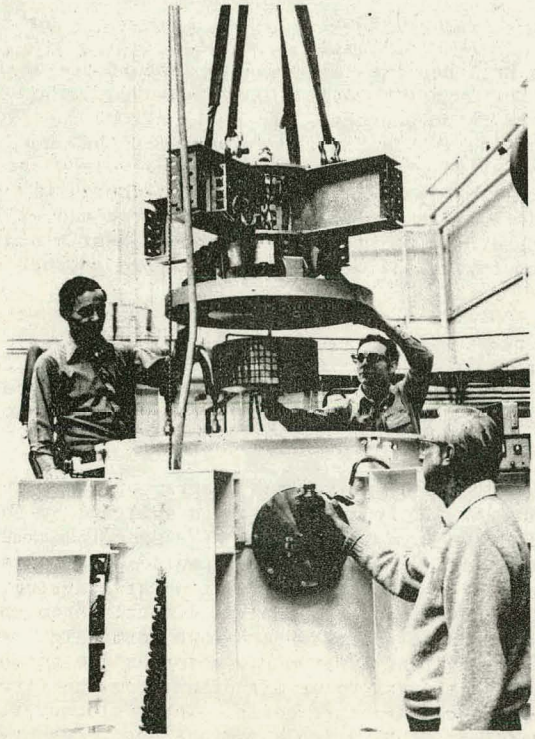

Figure 2
Flywheel assembly and vacuum tank.

is governed by the relative voltages of motor drive back EMF of armature and cycloconverter. For storing energy the motor drive voltage is always constrained to be equal to or greater than the back EMF. Back EMF is proportional to shaft speed. The cycloconverter input voltage is always equal to or less than the back EMF and is inversely proportional to the load.

The bearing magnetic flux (and lift force) is kept constant by means of the control coil driven from the axial lift servo. It takes just 4 W of power to lift the 400 lbs. of rotating mass. Long-term stability in position is excellent. Peak current for lift-off is supplied by a storage battery.

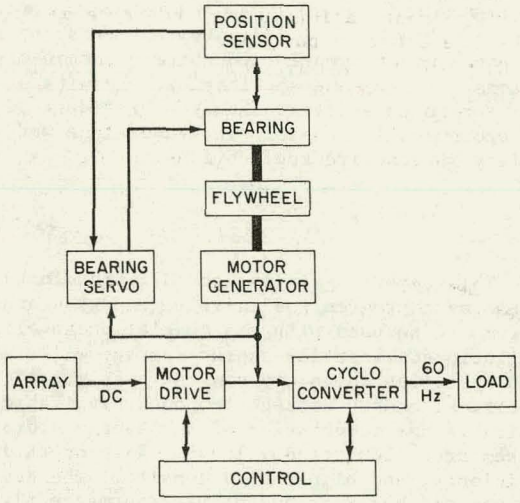

Figure 3
Flywheel system schematic.

Experimental Measurements

Installed instrumentation consists of transverse shaft position probes located in the upper and lower magnetic-bearing sections. Temperature thermistors are imbedded in the armature stator and attached to the mounting structure. Zero-speed vibration measurements were taken of the suspended shaft and flywheel. These tests confirmed the resonant modes which were calculated with a computer model of the system (3).

Power loss and efficiency were calculated from measured current and voltage in or out of the component being tested. In the case of AC power, the output power factor is assumed to be unity. It has been measured to be greater than 0.95. The energy added to or subtracted from the flywheel divided by the time interval for a speed change gives the power transferred. This method is used to find the idling or tare loss without input or output power. Power dissipated in the armature stator is calculated from winding resistance and the input or output current. The output current measured at the cycloconverter terminals must be corrected for the output transformation ratio to obtain the equivalent armature current in the unit. The temperature probes also serve as an approximate measure of power dissipation in the armature. The precision of measurement is approximately ± 3 W or 3% of the measured power, whichever is greater.

There was a fixed tare loss of 4 W at 7500 RPM, which increased to 6 W at 10,000 RPM. This is higher than anticipated due to circulating armature currents in the parallel halves of each phase. This loss averages 1.5% of the stored energy per hour for the steel flywheel. With the expected elimination of circulating armature currents and the installation of a 4-kWh high-performance rotor the tare loss would decrease to 0.4% of stored energy per hour.

Results from Operating Flywheel System

The flywheel was driven up in the vacuum tank to the minimum operating speed of 7500 RPM after passing through the whirl resonance at 40 Hz (2400 RPM). The motor drive has performed excellently up to 550-W input. The total input power efficiency is shown in Figure 4 and is a constant 92%. There is insignificant variation with power level or shaft speed. The total output power efficiency (output power divided by flywheel energy rate change) in Figure 4 is approximately constant at 82%, with a slight falling off at low power. This lower efficiency is due primarily to the poor waveform and power factor on the input side of the cycloconverter resulting in a comparatively large reactive power transfer between the cycloconverter and armature windings. The throughput power efficiency is about 75% for power over 200 W, but falls to ≃60% at low power. Methods to improve the low power efficiency are being investigated. The cycloconverter has been tested to 700-W output and has powered a variety of small AC appliances. The output waveform is excellent with current harmonic distortion of 0.5%.

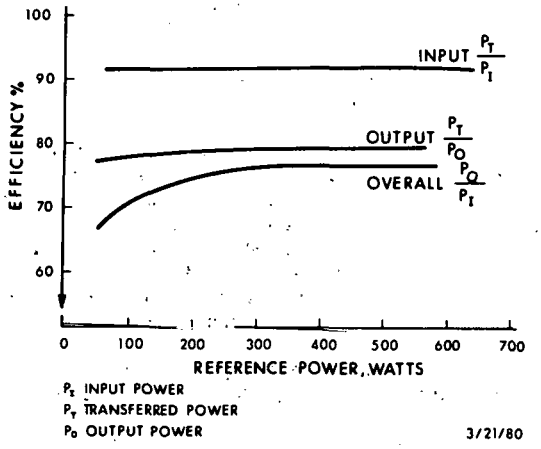

Figure 4
Measured flywheel efficiency.

Table II lists the measured component and system total efficiency. The total efficiency is close to the 73% predicted for the completed 40-kWh unit. For comparison, the expected efficiencies for a deep-discharge storage-battery system are shown to be similar.

An alternative output system, consisting of a rectifier with either a 60-Hz utility-interactive or stand-alone inverter, is being completed and will be tested. Results will be reported at a later time.

MEASURED EFFICIENCY FLYWHEEL ENERGY STORAGE AND CONVERSION SYSTEM
vs
BATTERY INVERTER AND MAXIMUM POWER TRACKER SYSTEM

FLYWHEEL BASED SYSTEM		
DC MOTOR ELECTRONICS	94 PERCENT	
DC MOTOR	96	
AC GENERATOR	90	
BEARINGS AND TARE	95	(1 1/2% Stored Energy Per Hour)
GENERATOR ELECTRONICS	88	
TOTAL	68 PERCENT PER HOUR	

BATTERY BASED SYSTEM	
MAXIMUM POWER TRACKER	96 PERCENT
BATTERY	80
INVERTER	85
TOTAL	65 PERCENT PER HOUR

4/28/80

Table II

A difficulty encountered in operating the system was an unexpected 2-Hz whirl resonance which appeared at about 170 Hz (10,500 RPM). This oscillation increases slowly at this speed until radial stability is exceeded. An experimental investigation of the rotating system resonance spectrum is being conducted to find the cause of the observed whirl instability, but for the present, 10,000 RPM is the maximum experimental shaft speed.

Scaling Performance to 40-kWh-Peak Storage

It is expected that the operating efficiencies for the 40-kWh system components will be equal to or higher than those of the reported 1/10-scale system. Efficiencies should improve with increasing size, especially the tare loss which would be 0.3% per hour energy loss. Table III lists the expected fixed losses and the operating efficiency for the residential scale system. The results of the 1/10-scale flywheel system tests, when scaled to the 40-kWh size, indicate that the performance goals are technically achievable.

RESIDENTIAL UNIT ESTIMATED LOSSES
40 kWh, 8 kW DC, 10 kW AC

FIXED LOSS	200 WATTS (2%of Full Load)
STORAGE LOSS	0.3% PER HOUR
INPUT ELECTRONICS:	
FULL LOAD	8%
HALF LOAD	7%
OUTPUT ELECTRONICS	
FULL LOAD	8%
HALF LOAD	7%
M/G LOSS (Input-Output)	
FULL LOAD	4%
HALF LOAD	2%

Table III

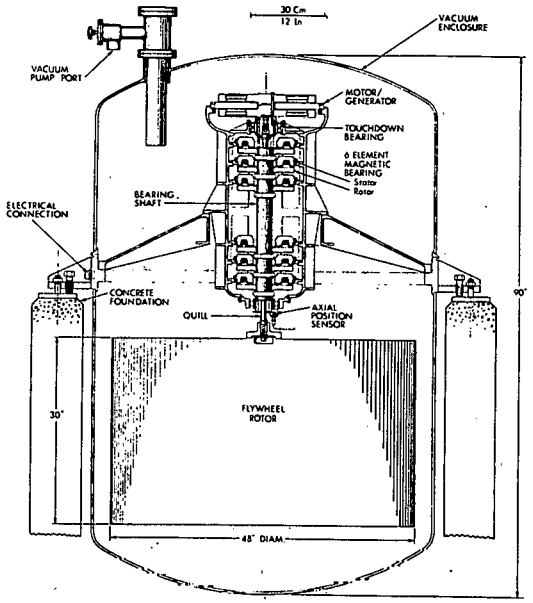

Figure 5
Residential flywheel energy storage unit.

MANUFACTURING COST ESTIMATES[1]
40 kWh, 8 kW
FLYWHEEL ENERGY STORAGE UNIT
• 10,000 UNITS PER YEAR 1980 TECHNOLOGY AND DOLLAR COSTS

ORGANIZATION	THEODORE BARRY	GARRETT AIRESEARCH	KELSEY-HAYES RESEARCH	MIT LINCOLN LABORATORY[3]
FLYWHEEL ROTOR	4,000[2]	4,000[2]	4,000[2]	5,000
MOTOR-GENERATOR	2,200	2,100	2,300	1,200
MAGNETIC BEARING ASSEMBLY	2,600	4,100	5,100	2,500
VACUUM SYSTEM AND ENCLOSURE	2,400	1,100	1,500	1,200
ELECTRONICS	1,200	3,500	2,600	1,800
SYSTEM CHECKOUT	200	500	1,200	-
INSTALLATION	1,000	1,500	900	800
SUB TOTAL	13,600	16,800	17,600	12,500
MANUFACTURING MARKUP AND DISTRIBUTION	3,400	5,000	2,700	-
TOTAL	17,000	21,800	20,300	-

(1) PRELIMINARY
(2) FLYWHEEL COST SPECIFIED BY MIT LINCOLN LABORATORY
(3) A.R. MILLNER, A FLYWHEEL ENERGY STORAGE AND CONVERSION SYSTEM MIT LL REPORT DOE-1074-48

Table IV

Results of 40-kWh System Cost Studies

Estimating the cost of manufacturing and selling inertial energy storage systems is perhaps more important than achieving technical performance goals. Figure 5 is a design layout of a residential-size system. Cost studies of the 40-kWh system based on this design have been done by three industrial contractors. Table IV presents the preliminary results of this work for the major components in quantities of 10,000 units per year. An estimate previously made by Lincoln Laboratory is shown for comparison although no figures for checkout or markup are included. These costs are based on the present design with current (1980) technology. Large cost differences between the different estimates for specific components are evident. Analysis of the cost studies is in progress to resolve the reasons for differences and to present a comprehensive summary of the studies. Redesign to reduce the number of parts and simplifying fabrication and assembly has been suggested as a first step. Material substitution is another cost-cutting technique. This is particularly applicable to the high-cost samarium-cobalt permanent magnet. It is estimated that these improvements could reduce costs by 30% or more, so that second-generation system costs are expected to be less than those shown in Table IV.

RESIDENTIAL FLYWHEEL SYSTEM COST ESTIMATES
1980 DOLLARS

	"HIGH" 1980 TECHNOLOGY ($)	"MEDIUM" 1985 HIGH ESTIMATE ($)	"LOW" 1985 LOW ESTIMATE ($)
STORAGE CAPACITY $/kWh	375	200	120
INPUT $/kWDC	130	90	40
OUTPUT $/kWAC	270	183	60
20 kWh TOTAL AT 8 kW	10,300	6,200	3,200
40 kWh TOTAL AT 8 kW	17,800	10,200	5,600

Table V

The rotor is the most expensive single part. Epoxy-impregnated filamentary rotors have undergone considerable development, with an estimated quantity production cost of $140 per kWh stored. Alternative rotor designs made with unbonded filaments (Kevlar, glass or steel) or amorphous metal ribbon (METGLAS)* are under development (4) and present the possibility of attaining $50 per kWh in production.

The 40-kWh design is being upgraded to incorporate suggestions and recommendations from the industrial cost studies. Attention is being directed to the other costly components: the magnetic-bearing assembly, the motor generator, and the electronics package.

Flywheel Energy Storage Economics

To be economically attractive for photovoltaic systems, flywheel energy storage must be appropriately sized to the array power and be available at a price that a buyer is willing to pay. A range of cost estimates for a flywheel system is shown in Table V. The "high" 1980 estimate is based on the cost studies summarized in Table III. The "medium" and "low" 1985 technology costs represent probable and optimistic cost estimates for a flywheel system with 1985 technology. These subsystem and total costs are used in the economic analysis to follow.

*R Allied Chemical Corporation

A system-worth analysis conducted by the MIT Energy Laboratory (5) considered the economic feasibility of energy storage with photovoltaics input in both utility-interactive and stand-alone family residence with an 8-kW-peak PV array in various operating modes and to make a determination of the sensitive financial parameters which would affect market penetration.

The Break-Even Capital Cost (BECC) is defined as the benefits (value of electricity displaced) less cost over the system life-time and includes the discount rate.

The System BECC must account for 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 BECC 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 MIT Energy Laboratory report 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 (Figure 6a). For the same size array, this figure increases to \$13,500 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. Assuming PV modules at the 1985 cost goal of \$.70 W peak (1980\$) and including BOS costs, flywheel BECC is \$300/kWh for 20-kWh available storage capacity (Figure 6b). Note that worth value is above the preliminary medium cost estimate of Table V. In general, the addition of storage serves to increase the optimum capacity of installed PV when hardware costs are assumed low enough to yield a positive return on investment. Depending on flywheel and other BOS cost assumptions, at some low utility buyback rate, the addition of storage capacity effects an increase in investment net benefits.

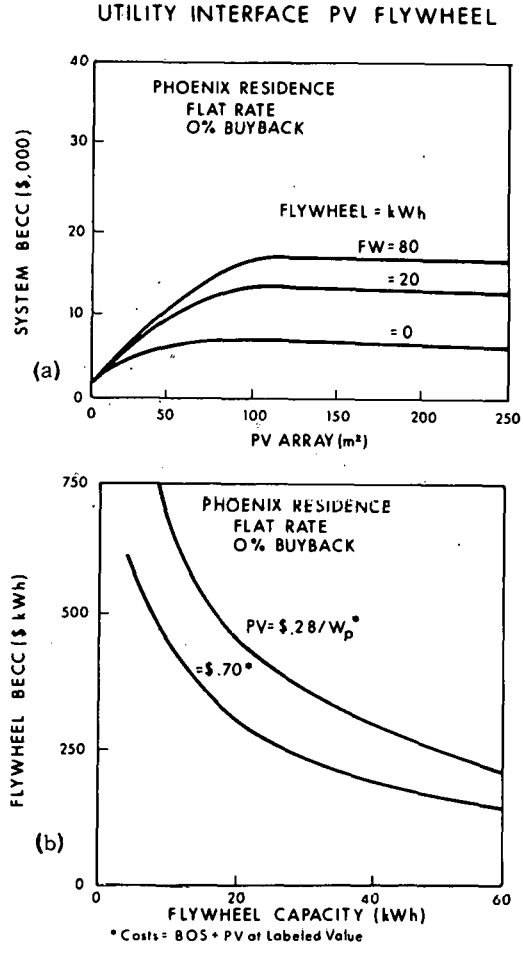

Figure 6a. System BECC vs. PV array.
Figure 6b. Flywheel BECC vs. capacity.

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, Figure 7). 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.

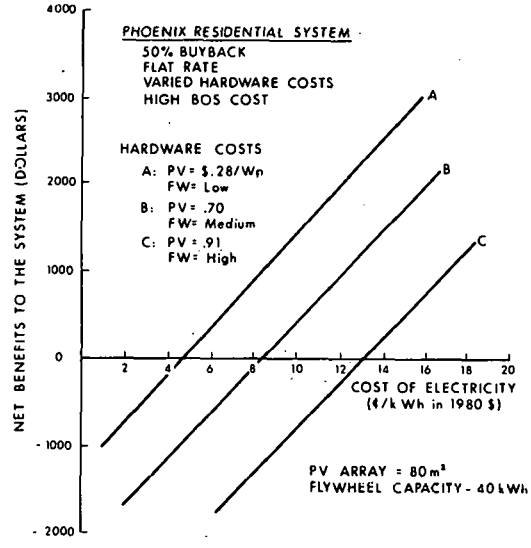

Figure 7
Utility interface PV and flywheel system new benefits vs. cost of electricity.

In the stand-alone (non-grid-connected) applications, optimum configuration sizing for the PV and flywheel (Figure 8) was found 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. The optimum size of a flywheel and PV system is highly sensitive to desired service reliability.

500-kWh, 100-kW Load Center

The characteristics and fabrication costs of a large 500-kWh inertial-energy-storage load center are based on geometric and energy scaling relationships derived from the 40-kWh residential system

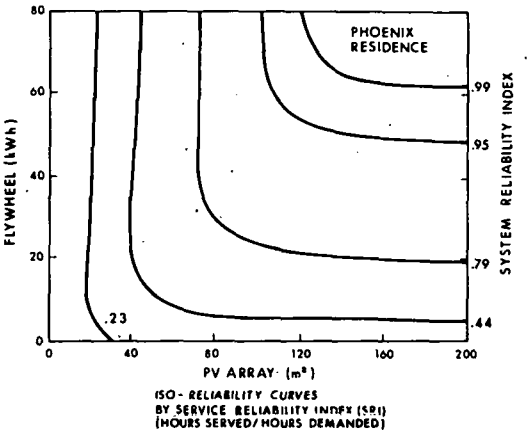

Figure 8
Remote stand-alone residential system: PV and flywheel only.

design (6). Obviously, a simple scaling in size is not a substitute for an engineered design, but it can form a basis for rudimentary fabrication cost estimates and suggest important features to be included in a 500-kWh energy-storage-system design.

The industrial cost studies included scoping estimates of the 500-kWh load center which are summarized in Table VI. The MIT Energy Laboratory user-worth study described above also analyzed a load center typified by a PV-powered apartment complex with energy storage.

100-kW LOAD CENTER
1980 TECHNOLOGY
COST ESTIMATE

STORAGE CAPACITY $/kWh		340
ELECTRONICS $/kW		250
500 kWh / 100 kW	TOTAL	$195,000
UNIT COST TOTAL $/kWh		390

Table VI

The preliminary results of the user-worth study reflect the same conclusions found for residential energy storage, i.e.: that there are diminishing returns for increased storage capacity and that the inclusion of storage has the effect of increasing optimum PV capacity. The results also predict break-even capital costs for the load center to be much lower. This indicated difference in costs requires further investigation because of the rudimentary character of the design upon which estimates were based. A detail design for a 500-kWh energy-storage system is needed to obtain accurate cost estimates and the basis of the economic model must be reviewed for appropriateness of the application.

Conclusion

Results obtained to date indicate that flywheel energy storage and conversion systems can be built with good performance characteristics of high throughput efficiency and low fixed losses. To meet the 1985 flywheel cost goals will require further refining of the residential flywheel design present here. When 1985 cost estimates are met, the worth of the system is greater than the cost for residential stand-alone applications and for utility-interactive applications with low buy-back rates.

Acknowledgment

Designing, overseeing construction, and check-out of the electronics was excellently done by Neil Rasmussen. This project was supported by the Photovoltaic and Energy Storage branches of the Department of Energy.

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