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PERFORMANCE TESTING AND ECONOMIC ANALYSIS OF A PHOTOVOLTAIC FLYWHEEL ENERGY STORAGE AND CONVERSION SYSTEM* ** +

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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, is described. Performance results of prototype testing are given and indicate that this system is the equal of or superior to battery-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 some 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. In contrast to storage batteries, inertial energy storage systems have the capacity for short duration high discharge rates without degradation. This characteristic can be used to advantage in a residence where a high peak to average load exists. In industry, high demand charges can be reduced by using inertial energy storage to supply peak power needs. 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 is 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 small 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.

DESCRIPTION OF 1/10 SCALE LABORATORY SYSTEM

The features and characteristics of this system 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 principle components are:

- Flywheel rotor
- Motor/generator
- Six magnetic bearings
- Shaft
- Quill
- Touchdown bearings

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DISCLAIMER

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TABLE I
FLYWHEEL SYSTEM PARAMETERS

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	220 C.T.	440
MAXIMUM OUTPUT CURRENT	RMS AMPS PER PHASE	5.6	45	130
PHASES	NO.	1	1	3

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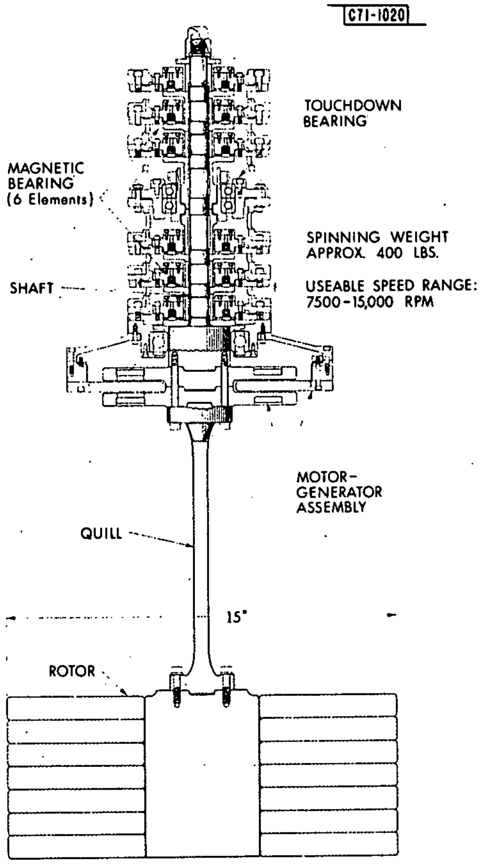

Figure 1.
1/10-scale experimental flywheel.

The touchdown 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 the rotor is not perfectly balanced. The present flywheel, which has a specific energy of 10 Wh/kg, is made from steel discs pressed onto a hub. One or more advanced design ($\sim$40 Wh/kg) flywheel rotors of potentially low fabrication cost will be procured and will be substituted for the steel rotor to test a configuration typical of a residential energy storage system. The steel rotor is balanced within 1.3×10^{-6} kgm, however the quill mounting is designed to operate with an imbalance up to 4.3×10^{-4} kgm.

Figure 2 shows the complete assembly ready to be placed in the vacuum tank. A thick enclosure surrounds the steel flywheel as a safety shield for containment in the unlikely event of a quill or flywheel failure. This heavy shield would be completely unnecessary for a filamentary composite rotor which has a characteristically benign failure mode should a failure take place. 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 SCR motor drive into the motor/generator armature windings. Hall generators provide motor phase signals for unidirectional rotation at starting. The ouput cycloconverter is powered from the motor-generator armature terminals. Power can flow directly from the motor bridge to the cycloconverter or be put into or withdrawn from the flywheel through the armature coils. The cycloconverter transforms the variable voltage and frequency three-phase motor AC to single-phase 60 Hz, 117 V. Power flow is governed by the relative voltages of the motor drive, the back EMF of the armature and the cycloconverter. For storing energy the motor drive voltage is always constrained to be equal to or greater than the back EMF which is proportional to shaft speed. The cycloconverter input voltage is always equal to or less than the back EMF. The cycloconverter type of frequency changer was selected for the 1/10-scale Laboratory system because of its potential for stand-alone frequency stability and adaptability in using less expensive SCR semiconductors.

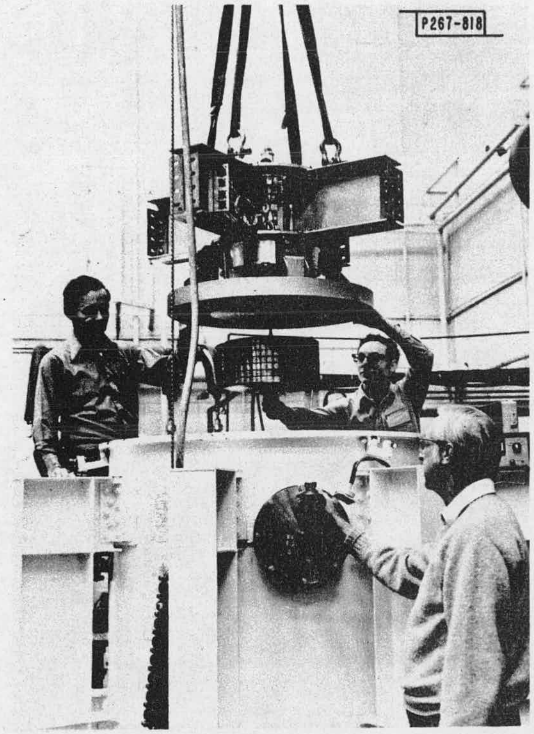

Figure 2
Flywheel assembly and vacuum tank.

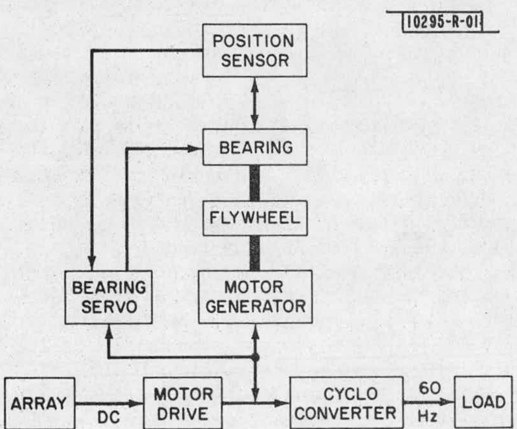

Figure 3
Flywheel system schematic.

The bearing servo functions to control the axial position and thus maintains constant magnetic flux (and lift force) in the air gap. An error signal from the axial position probe modulates the current in the bearing flux control coil to maintain equilibrium. Long-term position stability has been found to be excellent. Peak current for lift-off is supplied by a storage battery.

It is important to note that this is an experimental/developmental energy storage system. The experience gained in building and operating the system will be used in the design of prototype residential units.

EXPERIMENTAL MEASUREMENTS

Diagnostic instrumentation consists of transverse shaft position probes located in the upper and lower magnetic bearing sections. In addition, temperature thermistors are imbedded in the armature stator and attached to the mounting structure. Other measurements of power, voltage, wave shape, etc., were taken with standard laboratory instruments. After completing the flywheel assembly, initial lift-off of the magnetic bearings was achieved without difficulty. Zero-speed-vibration characterization 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, which has been measured to be greater than 0.95, is assumed to be unity. The measurement precision is approximately $\pm$ 3 W or 3% of the measured power, whichever is greater.

Results of initial measurements indicate that there is a fixed loss, exclusive of magnetic bearing power, of 4 W at 7500 rpm, which increases to 6 W at 10,000 rpm. This is a greater loss than anticipated and is at least partially 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, this component of the tare loss would decrease to 0.4% of stored energy per hour.

RESULTS FROM INITIAL TESTS

Using the motor drive, the flywheel was spun up in the vacuum tank to the minimum operating speed of 7500 rpm after passing through the whirl resonances at 40 and 70 rps. The motor drive has performed excellently up to 550-W input and the motor-commutation circuit transfer from forced to self-triggering works smoothly. The total input power efficiency, shown in Figure 4, was found to be a constant 92% with no significant variation with power level or shaft speed. The total output power efficiency (output power divided by flywheel energy rate change, Figure 4) was found to be approximately constant at 80%, with a slight falling off at low power. This lower efficiency is due primarily to the poor wave form and power factor on the input side of the cycloconverter at the generator frequency, resulting in increased reactive power transfer between the cycloconverter and generator. The indicated throughput power efficiency is about 75% for outputs of over 200 W but falls to ~60% at low power. This efficiency was measured with the maximum energy transferred to or from the rotor limited to 50% of either the input or output power. Any energy transferred was credited to input or output according to sign.

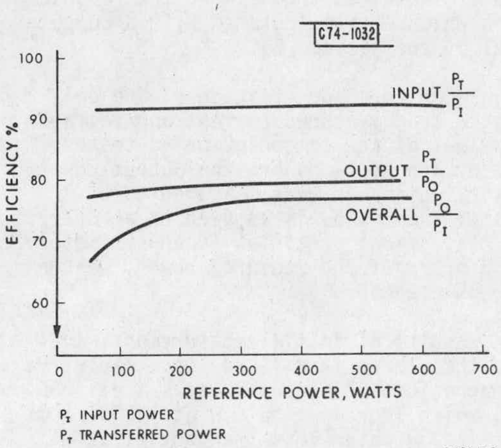

Figure 4
Measured flywheel efficiency.

There is a measureable enhancement in throughput efficiency with simultaneous operation of input and output electronics compared to multiplying separate input and output measurements. 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%.

Table II lists the measured component and system total efficiency. For comparison, the expected efficiencies for a deep discharge storage battery system are shown to be similar.

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TABLE II

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

4/28/80

As an alternative to the cycloconverter, a system consisting of a rectifier, a DC-DC down converter, and either a 60-Hz utility-interactive or a stand-alone inverter, is being completed and will be tested. Results will be reported at a later time. Previous experience with inverters has shown that conversion efficiencies of 80 to 90% can be achieved.

During the course of the testing, an unexpected excitation of the 2-Hz whirl resonance was encountered within the operating range at about 170 rps (10,000 rpm). With sustained operation at this speed, the amplitude of the 2-Hz resonance increased slowly until bearing touchdown was encountered. An experimental investigation of the rotating system resonance spectrum is being conducted to find the cause of the observed whirl instability. The damping value built into the present magnetic bearings is very small at 2 Hz and is apparently insufficient to suppress this frequency. Additional damping is being added to the system to correct this condition. Under experimental conditions, the bearing system has remained stable against external vibrations (< 100 Hz) with peak amplitudes of 0.0002 m of 0.001 rad ($\sim$0.03 arc minute). These values are larger than amplitudes of commonly found earth vibrations. Since there are no spin resonances in the operating speed range, exciting a resonance from external vibrations is not expected to occur.

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 drop to 0.3% per hour energy loss. Table III lists the expected fixed losses and the operating efficiency for the residential-size system. The results of the 1/10-scale flywheel-system tests, when scaled to the 40 kWh-size, indicate that the performance goals are achievable.

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TABLE III
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%

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. Based on this layout, cost studies have been done by three industrial contractors using the 1/10-scale flywheel details scaled up to the required size for manufacturing cost estimates. 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 system checkout or markup are included. These costs, based on the present design with current (1980) technology, should be considered as upper limits. Large cost differences between the different estimates for specific components are evident. Investigation into the basis for estimating a given component shows a variety of approaches but the final cost totals are fairly close so the variations in component costs tend to average out. 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, thus simplifying fabrication and assembly, has been suggested as a means to decrease costs. Material substitution is another cost-cutting technique which is particularly applicable to the high-cost samarium-cobalt permanent magnets. 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. These options are being investigated.

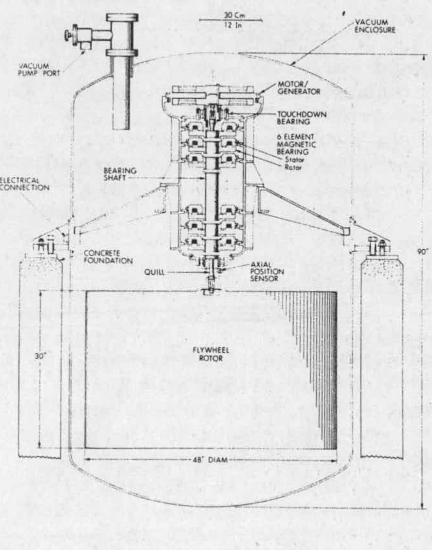

Figure 5
Residential flywheel energy storage unit.

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TABLE IV.

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 COO-4094-48

In considering areas of cost reduction, the rotor stands out as the most expensive single part. High-energy density rotors are required to make inertial energy storage cost competetive with other storage systems. One possibility is epoxy-impregnated filamentary rotors, which have undergone considerable development and have 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 also under development [4] and present the possibility of attaining $50 per kWh in production. This latter figure would result in a halving of the rotor cost shown in Table V.

The power necessary to maintain the vacuum surrounding the rotor is a requirement which directly affects system efficiency. Surface outgassing will be great enough to require pumping so as not to exceed an absolute pressure of $\sim 10^{-3}$ torr, where air drag is unimportant. This can be done either periodically or continuously, or alternatively, the vacuum enclosure can be sealed off and a getter or adsorption pump used with initial roughing accomplished with a temporary pumping system. The volume of gas to be pumped is small (≤ 10 l/s) and the choice of a pumping method will depend on the cost and reliability of the pumping system, including the average power required to operate it.

* ® Allied Chemical Corporation

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

FLYWHEEL ENERGY STORAGE ECONOMICS

To be economically attractive for photovoltaic PV 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 IV, including an allowance for cost-reducing manufacturing improvements expected in the second-generation residential flywheel systems.

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TABLE V

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	220	185	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

The "medium" and "low" 1985 technology costs represent probable and optimistic cost estimates based on improved component design with continuing system development for a flywheel system with 1985 technology. These subsystem and total costs are used in the economic analysis which follows.

A system-worth analysis conducted by MIT Energy Laboratory [5] considered the economic feasibility of energy storage with photovoltaic input in both utility-interactive and stand-alone installations. The objectives of the report were to determine optimal flywheel sizing for a single-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 results of this analysis are presented as a value which is the difference between the benefits and the cost to the homeowner of a PV installation. This Break-Even Capital Cost (BECC) is defined as:

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

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, i = Assumed lifetime of the system: 20 years.

r = Discount rate. (The true cost of borrowing money.)

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 (BOS) costs, including mounting, electrical wiring of the PV modules, and all maintenance over the life of the system.

The Flywheel BECC includes the costs associated with power conditioning and is the system BECC less the cost of non-flywheel components such as PV modules.

The MIT Energy Laboratory report showed that for a utility-interactive residence in Phoenix with a flat-rate price structure and 0% buy-back from the utility, system BECC is \$5,000 with an 80-m^2 array and no flywheel (Figure 6a). This figure increases to \$11,500 and \$13,000 for a system with flywheels of 20-and 40-kWh usable capacity, respectively. Flywheel BECC under the same conditions is a function of assumed balance-of-system costs

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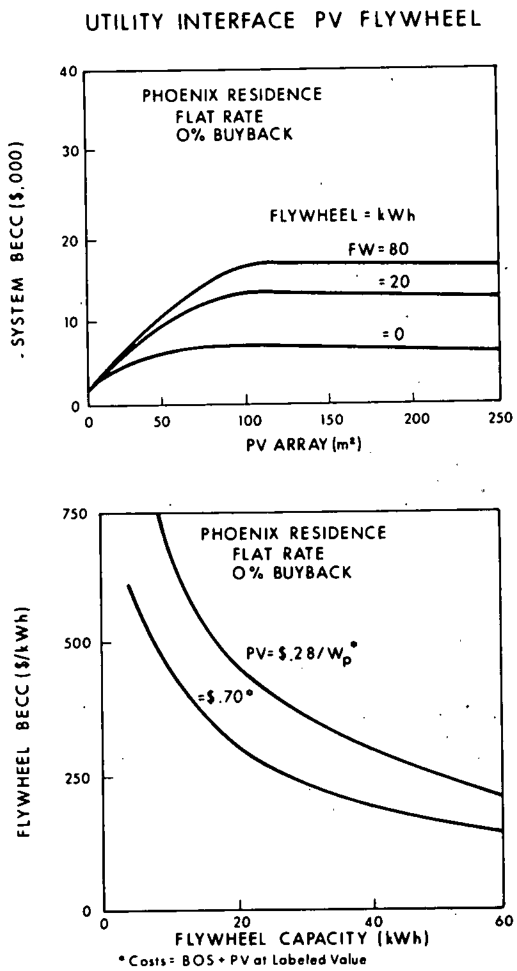

Figure 6a. System BECC vs. PV array.
Figure 6b. Flywheel BECC vs. capacity.

and PV module costs. For a 20-kWh-capacity flywheel and PV modules at the 1985 cost goal of $0.70 Wp (1980$) including BOS costs, the flywheel BECC is $300/kWh (Figure 6b). Note that this worth value is above the preliminary medium cost estimate of Table V showing that flywheels are an economical addition to a PV system when utility buyback rates are low.

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. When storage is dedicated to the PV array alone, it is shown to have the greatest value when buyback 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. 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 0.09/kWh (starting 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 discount rate, r, is an important parameter in influencing system worth.

For stand-alone (non-grid-connected) applications, the optimum configuration and sizing for the PV and flywheel (Figure 8) was found to be 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. In addition, the optimum size of a flywheel and PV system is highly sensitive to the desired service reliability. For stand-alone applications, an auxiliary generator is assumed to supply the power differential between that available from the PV system and storage and the requirements of the load.

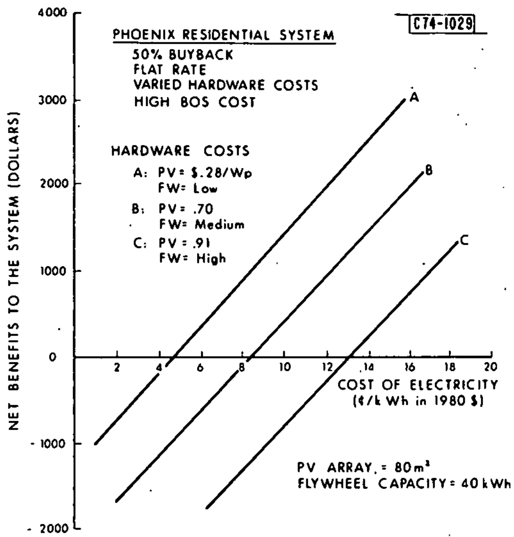

Figure 7
Utility interface PV and flywheel system new benefits vs. cost of electricity.

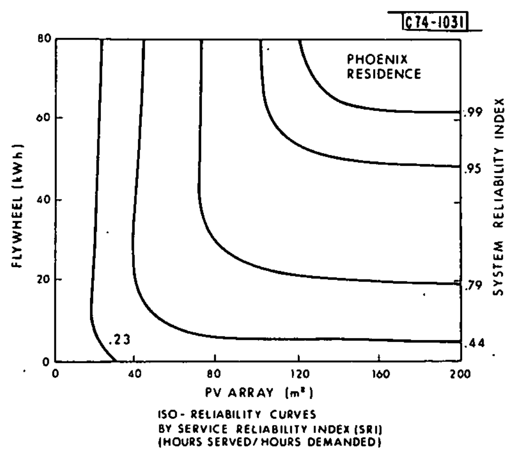

Figure 8
Remote stand-alone residential system: PV and flywheel only.

500-kWh, 100-kW LOAD CENTER

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

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TABLE VI
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

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 array size. The results also predict lower breakeven capital costs for the load center. This indicated difference in costs requires further investigation because of the rudimentary character of the design upon which estimates were based. A detailed 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 for this application.

CONCLUSION

Results obtained to date indicate that flywheel energy storage and conversion systems can be built with high throughput efficiency and low fixed losses. The 1985 flywheel costs goals will be met by further refinement of the residential flywheel design presented 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 buyback rates.

ACKNOWLEDGMENTS

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