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TECHNICAL PAPER #22

UNDERSTANDING ENERGY
STORAGE METHODS

By
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PREFACE

This paper in one of a series published by Volunteers in Technical
Assistance to provide an introduction to specific state-of-the-art
technologies of interest to people in developing countries.
The papers are intended to be used as guidelines to help
people choose technologies that are suitable to their situations.
They are not intended to provide construction or implementation
details. People are urged to contact VITA or a similar organization
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that a particular technology seems to meet their needs.

The papers in the series were written, reviewed, and illustrated
almost entirely by VITA Volunteer technical experts on a purely
voluntary basis. Some 500 volunteers were involved in the production
of the first 100 titles issued, contributing approximately
5,000 hours of their time. VITA staff included Maria Giannuzzi
as editor Julie Berman handling typesetting and layout, and
Margaret Crouch as project manager.

The author of this paper, Clyde S. Brooks, has been a VITA Volunteer
for many years. He holds a B.S. in chemistry and has done
graduate work at Duke University and Carnegie-Mellon University.
Currently, Brooks performs independent research consultancies in

applied physical chemistry. His experience includes coal chemical processing, chemical stimulation of oil recovery, and energy conversion processes. The reviewers of this paper are also VITA Volunteers. Paul J. Hauck has been a mechanical engineer for Westinghouse for the past 20 years. He designs piping systems and pressure vessels and operates and maintains pumps, motors, heat exchangers, valves, etc. LeGrand Merriman is an electrical engineer who worked for Westinghouse for 31 years. His duties included directing the installation, start-up and servicing of electrical equipment. Lester H. Smith, Jr., an electrical engineer, is a founding partner of an electrical consulting firm responsible for various medical, institutional, commercial, and residential projects in the United States.

VITA is a private, nonprofit organization that supports people working on technical problems in developing countries. VITA offers information and assistance aimed at helping individuals and groups to select and implement technologies appropriate to their situations. VITA maintains an international Inquiry Service, a specialized documentation center, and a computerized roster of volunteer technical consultants; manages long-term field projects; and publishes a variety of technical manuals and papers.

ENERGY STORAGE METHODS

By VITA Volunteer Clyde S. Brooks

I. INTRODUCTION

Energy storage capability is essential if the maximum economic advantage is to be gained from small power plants. Unless the power plant is operated at full load on a continual basis, there will be periods when there is a lower load demand upon the plant. As a result of this lower demand, excess energy will be generated by the plant. The use of an energy storage system will allow for the recapture of this surplus energy and its later use during periods of high demand.

This paper presents a critical review of the technical features, state of development, and economics of various energy storage systems and their compatibility with small power plants. The small power plants examined here have generation capacities within a range of 1 to 50 kilowatts (kW) and consist of systems such as windmills and small-scale hydropower.

Energy storage systems potentially compatible with small power plants include batteries, flywheels, pumped water, and compressed air.(*) In selecting an energy storage system for small power plants in developing countries, the most important factors to consider are storage capacity required; capital costs; operating costs; nature of storage/generation duty cycles; system complexity in terms of how easily the system can be built, operated, and maintained; hardware availability; form of energy recoverable from storage; conversion efficiency; and the country's current state of technical development in related fields.

In this examination of energy storage systems, emphasis will be placed on the overall technical features of the systems and their

comparative performance and efficiency. The characteristics of the various energy storage technologies are considered below individually and then compared with each other. Based on this comparison, recommendations as to the most promising storage systems for use in combination with small-scale hydropower and wind energy generators are made. It should be noted that the discussion of economic factors (e.g., operating costs) is based on data obtained for the most part from large power plants in highly industrialized countries such as the United States.

(*) Other more advanced energy storage technologies are beyond the scope of this paper.

One word of caution: It is beyond the scope of this paper to provide a detailed engineering or economic analysis of energy storage systems. A feasibility study will have to be performed for any given site. Nevertheless, this paper will aid in the selection of promising energy storage system that merit more detailed study.

II. SYSTEM ALTERNATIVE

Several energy storage systems will be examined in this section: batteries, compressed air, pumped water, and flywheels.

BATTERIES

Batteries are commonly used to store the electricity generated by

wind machines and small-scale hydropower plants. A typical system
couples the drive shaft of the power source to a direct current
(DC) generator. The rotating shaft produces mechanical energy,
which is converted to electricity by the generator. Excess electricity
can then be stored in banks of batteries.

Before choosing any generating and storage system, you must
determine how much power you will need. Tables 1 through 3 show
average annual power usage for electric home heating and appliances
in the range of 5,000-8,000 kilowatt-hours per year
(kWh/yr). A small wind power system of 5 kW, such as one currently
marketed by an American company, is estimated by the manufacturer
to provide about 1,0000 kWh/yr under average wind conditions.
Such a system would be more than adequate to meet the
energy requirements of an individual household in a highly industrialized
country such as the United States. (No attempt is made
here to specify the wind conditions essential for the economic
operation of windmills. But it is fairly well established that if
the wind velocity does not achieve or exceed 12 miles per hour
for most of the year, the siting of even a small wind machine
would be economically impractical.) Based on this estimate, even
a household with many appliances could generate sufficient excess
power to justify the cost of battery storage.

In order to determine the cost of a combination generation and
battery storage system, the capacity and number of wind or hydropower
generators would have to be established, as well as an
appropriate bank of storage batteries.

Proper design of battery storage capacity must be based on anticipated
excess power for storage and recommended battery charge
and discharge rates.

Table 1. Average Annual Energy Requirements of 110 Volt Electrical Appliances

Average Power Estimated
Required per Annual Energy
Appliance Consumption
 (Watts) (kwh)
* Food Preparation
Blender 385 15
Broiler 1,436 100
Carving Knife 92 8
Coffee Maker 894 106
Deep Fryer 1,448 83
Dishwasher 1,201 383
Egg Cooker 516 14
Frying Pan 1,196 185
Hot Plate 1,257 90
Mixer 127 13
Oven (microwave) 1,450 190
Range
with oven 12,200 1,175
self-cleaning oven 12,200 1,205
Roaster 1,333 205
Sandwich Grill 1,161 33
Toaster 1,146 39

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Trash Compactor 400 50
Waffle Iron 1,116 22
Waste Disposer 445 30


* Food Preservation
Freezer (15 cu ft) 341 1,195
Freezer (2 cu ft
frostless) 440 1,761
Refrigerator (12 cu ft) 241 728
Refrigerator (12 cu ft
frostless) 321 1,217
Refrigerator/freezer
 (14 cu ft) 326 1,137
 (14 cu ft frostless) 615 1,829
Low Energy Model
1973, 21 cu ft frostless
starting 2,480
running 320 1,200
* Health & Beauty
Germicidal lamp 20 141
Hair Dryer 381 14
Heat Lamp (infrared) 250 13
Shaver 14 18
Sun Lamp 279 16
Tooth Brush 7 0.5
Vibrator 40 2
* Home Entertainment
Radio 71 86
Radio/Record Player 109 109
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Television
black & white tube type 160 350
solid state 55 120
color
tube type 300 660
solid state 200 440
* Housewares
Clock 2 17
Floor Polisher 305 15
Sewing Machine 75 11
Vacuum Cleaner 630 46
* Lights
75 Watt bulbs (8 each) 600 864
* Laundry
Clothes Dryer 4,856 993
Iron (hand) 1,008 144
Washing Machine
 (automatic) 512 103
Washing Machine
 (non-automatic) 286 75
Water Heater 2,475 4,219
 (quick recovery) 4,474 4,811
* Comfort Conditioning
Air Cleaner 50 216
Air Conditioner (room) 1,565 1,889
Bed Covering 177 147
Dehumidifier 257 377
Fan (attic) 370 281
Fan (circulating) 83 43
```

Fan (rollaway) 171 138
Fan (window) 200 170
Heater (portable) 1,322 178
Heating Pad 65 10
Humidifier 177 163
* Tools
1/4" drill 250 2
Sabre Saw 325 1
Skill Saw 1,000 5
Typewriter 40 7
Water Pump (1/3 HP) 420 150
3" Sander, Belt 770 10
* Electric Home Heating [a]
Measured Living Area
1,000 Sq. Ft. 17,000 16,300
1,500 Sq. Ft. 21,500 20,800
2,000 Sq. Ft. 26,000 25,500

Sources: Electric Energy Association, 90 Park Avenue, New York, New York; Henry
Clews, "Electric Power from the Wind," Business Week, March
24, 1973.

Note: The estimated annual kilowatt-hour consumption of the electric appliances
listed in this table are based on normal usage. When using these figures for
projections, such factors as the size of the specific appliance, the
geographical area of use, and individual usage should be taken into
consideration. Please note that the wattages are not additive since all units
are normally not in operation at the same time.

[a] Based on figures published by local utilities for electrically heated homes.

Table 2. Typical Home Power Usage

	Average Power Required per Appliance (Watts)	Daily Energy Consumption (kWh) [a]
Type of Appliance		
Refrigerator:		
14 cu. ft. frostless	615	5.00
1/2 HP oil burner	400	3.21
Lights (100-watt bulb)	100 x number of lights	5.60
TV color tube	300	1.80
Coffee maker	900	0.60
Toaster	1,146	0.40
Frying pan	1,196	0.60
Clocks (3)	2	0.14
Hot plate	1,257	0.42
Vacuum cleaner	630	0.63
Dishwasher	1,201	0.80
Clothes washer	512	0.25
Clothes dryer	4,856	2.41
Total		21.86

Source: Grumman Aerospace Corporation, Living with Wind Power
(Bethpage, New York, 1975), p. 4.

[a] 21.86 x 30 = 655.80 kWh per month; 655.80 x 12 = 7,869 kWh per year.

Table 3. Planned Home Usage

**Average Power Daily Energy
Required per Consumption
Type of Appliance Appliance (Watts) (kWh) [a]**

**Refrigerator: 21 cu. ft.
frostless Philco Ford 320 2.56
1/2 HP oil burner 400 3.21
Lights (40-watt bulb) 40 x number of lights 2.24
TV color solid state 200 1.20
Coffee maker 900 0.60
Toaster 1,146 0.40
Frying pan 1,196 0.60
Clocks (3) 2 0.14
Hot plate 1,257 0.42
Vacuum cleaner 630 0.63
Dishwasher 1,201 0.80
Clothes washer 512 0.25
Clothes dryer 4,856 2.41**

Total 15.46

Source: Grumman Aerospace Corporation, Living with Wind Power
(Bethpage, New York, 1975), p. 4.

[a] 15.46 x 30 = 463.80 kWh per month; 463.80 x 12 = 5,565.5 kWh
per year.

Specific questions that must be considered in designing such a
system are:

1. The types of electrical loads to be served by the system.
Whether direct current (DC) power only is required or
whether inverters must be included to complete the conversion
of stored DC electricity to alternating current
(AC). If the loads to be served are largely incandescent
lighting and heating, the output of the battery system
may remain direct current since incandescent lamps and
most heat producing equipment (space heaters, toasters,
irons) operate successfully on DC or AC. If the loads are
motors (pump drives, fans) of 1/2 horsepower and larger
or are communication equipment (radio and television
transmitters), inverters will be required as a part of
the storage system.

2. Whether a multiple power generation and multiple user
system is required. In most applications, a single prime
mover (windmill, turbine) will be required. However, if
multiple generators are employed, additional equipment

must be added to the system to enable paralleling of
electrical output. Multiple battery installations accompany
multiple generators as a general rule. For most
applications, a single prime mover, generator, and battery
bank will be preferred due to the simplicity of
installation, operation, and maintenance. Where extended
systems to serve more loads are desired, an increase in
capacity of the single system is the preferred approach.

3. Whether commercial hardware with established performance
characteristics is available. While it is possible to
assemble and fabricate a system from unrelated components,
the chances for successful operation will be enhanced
by using factory-assembled systems that have been
designed to match one another. A compromise in development
of the system would be to purchase and match groups
of commercial equipment. For example, a prime mover and
generator could be purchased and matched to a battery
bank, charger, and inverter.

4. Energy source characteristics, by day and by season. If
wind is the source of energy, its availability must be
determined, on average, for each day of each season. Its
velocity must also be estimated. If water is the source,
the same determinations must be made. Whether the energy
source is wind or water, these determinations must be
made in advance of designing the storage system. For
example, winds usually vary in velocity throughout the
day; during periods of low or no wind, the battery system

must be capable of making up the electrical energy the generator cannot produce during those periods. Similarly, knowing the length and time of occurrence of strong wind velocity will enable a designer to estimate how large a battery bank can be recharged.

5. Electrical load demand characteristics, by day and by season. The daily, weekly, and seasonal characteristics of the electrical load demand must be determined in advance of design of the system. To make electrical energy available at the moment it is needed requires an accurate estimate of how much is needed at what hours of which days during the year. For example, if water is to be pumped for irrigation, it will likely be a continuous load throughout certain seasons. Lighting loads will appear only in the early morning, evenings, and early hours of the night, but these loads will appear every day of the year even though the number of hours will vary each day. If space heating will be provided, it will likely appear as a load on the system only during a specific season.

The costs of a given system will have to be estimated, based on discussions with specific hardware suppliers regarding:

* performance specifications for the system;
* capital costs;
* shipping costs;
* power consumption and efficiency of operation;

* labor commitment required for system operation; and
* anticipated life of hardware components.

Having stated these requirements for initial system design and
pricing, it is clear that an experienced electrical engineer
should be selected to plan and oversee system installation. Once
a system has been assembled, semi-skilled laborers could become
operators, but there should be supervision by someone sufficiently
trained in the component hardware to conduct all necessary
routine maintenance.

No attempt is made here to specify hardware, which must be done
by the electrical engineer selected for system design, in collaboration
with specific hardware suppliers.

There are many types of storage batteries. Many of these, in
various stages of development, have performance characteristics
superior to the lead-acid battery. However, in terms of overall
demonstrated performance, cost, useful life, and commercial
availability, the lead-acid battery is the most conservative and
economical choice (see Table 4). Industrial lead-acid batteries
with power ratings to 225 ampere-hours and regeneration life
cycles to about 1,800 are available commercially.

Table 4. Comparison of Today's Storage Batteries

Battery Density By: [b]

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Cost [a] Weight Volume Life[c]
Battery Type (Dollars/kWh) (Wh/kg) (kWh/cu.meter) (Cycles)

Silver-Zinc 900 120 310.8 100/300
Nickel-cadmium 600 40 127.1 300/2,000
Nickel-iron 400 33 49.4 3,000
Load-acid: 50 22 91.8 1,500/2,000
```

Source: D.L. Douglas, "Batteries for Energy Storage," Symposium on Energy Storage, 168th National Meeting, American Chemical Society, Preprint Fuel Division, Vol. 19, no. 4 (Washington, D.C.: ACS, 1974), pp. 135-154.

[al Cost to the user.
[b] Battery capacity is inversely related to rate of discharge. The values shown are for the 6-hour rate.
[c] Cycle life depends on a number of factors, including depth of discharge, rate of charge and discharge, temperature, and amount of overcharge. Range shown is from most severe to modest duty.

COMPRESSED AIR

The drive shafts of wind power systems or small-scale hydropower plants can be linked to conventional gas compressors and used to store air at pressures on the order of 600 pounds square inch (psi). The compressed air can be depressurized subsequently

through conventional turbines to generate electricity, or it can be linked through gearing for use of the stored energy to power any mechanical machinery driven by a rotating shaft or drive belt. Efficiencies of 75 percent can be attained for utilization of the stored energy.

The compressed gas can either be air or fuel gases (e.g., natural gas or hydrogen). However, for purposes of this paper, the discussion will relate to compressed air only.

The economics of storage will be most favorable if existing underground storage capacity such as depleted oil fields, coal mines, or aquifers can be used. Underground storage of natural gas is a widely used and economical technology. If underground storage containers are used, costs are minimized, but a certain amount of unrecoverable residual gas loss (20 percent or more) will have to be accepted as a penalty. High pressure gas can also be stored in steel containers. However, if new containers must be purchased, the capital costs for a large power plant may be greatly increased. For small plants, steel tanks are a practical alternative.

PUMPED WATER

Pumped water, stored above ground or underground, can also be used as an energy storage device in combination with either small-scale hydro or wind energy generators. Pumped water as an aid in peak leveling for electric hydropower generation has been used in the United States since the early 1930s. The options for energy retrieval are quite similar to compressed air with perhaps

5-15 percent' less overall efficiency than that obtained from compressed air. Underground storage in various types of depleted mines or aquifers offers some cost advantages over surface storage, since the costs of reservoir construction can greatly increase the total cost of power plant construction.

Pumped water storage in a special reservoir can be provided during high river flow periods. During spring thaws or rainy seasons the river flow may be able to develop more power than the electrical system can consume. The stored water may then be released for power generation during future peak load periods or dry seasons. Extensive areas of land must be flooded to provide sufficient storage or pondage for a hydroplant. Losses due to evaporation, irrigation, and infiltration into the soil are difficult to estimate and may vary from time to time. When evaporation rates are high, a shallow pond with a large surface area is disadvantageous.

The available data on costs for pumped water storage systems are derived entirely from megawatt size power plants. For small power plants, applicable cost data will have to be calculated for any given site considered.

FLYWHEELS

The flywheel is a device that permits storage of energy in the form of a rotating wheel. Mechanical energy such as that from the rotating shaft of a wind energy or hydropower system can be converted to the kinetic energy of a low-friction flywheel for

storage. Surplus energy from a wind or hydropower system stored
in the rotating flywheel can be subsequently recovered as rotating
shaft mechanical energy or possibly converted to electrical
energy via a generator to satisfy peak demands.

The energy stored in the flywheel is given by the formula
W = 1/2 [Iw.sup.2] where "W" is the stored energy, "I" is the moment of
inertia of the flywheel, and "w" is the angular velocity in radians
per second of the flywheel. One of the attractive features
of the flywheel is its adaptability to a wide range of energy
requirements for small power plants in the 1-50 kW range. The
mass of the flywheel and its angular velocity can be varied to
obtain this range of storage capacities. Efficiencies are potentially
high and energy densities of 66 watts/kilogram can be attained
for power peaking rotation speeds of 1,800 to 3,600 revolutions
per minute (rpm) by gearing to the rotating shaft of
small power generators, whether wind or hydro.

Successful performance requires careful design and high-strength
materials. Steel has been used for years, but modern composites,
such as metal alloys, glass fiber, and polymer/carbon fiber, provide
the strength required for coherence during extended duty
cycles to prevent catastrophic failure of the flywheel at high
rotation speeds. Actually, wood and bamboo are low-cost, high-strength
flywheel materials that are economically competitive
with the synthetic composite materials cited above.

The flywheel is quite competitive with alternative energy storage
systems for small power plants in terms of efficiency, storage

energy density, and cost. Small flywheels that provide 30-1,000
watt-hours (Wh) of energy storage for around $50-100/kW
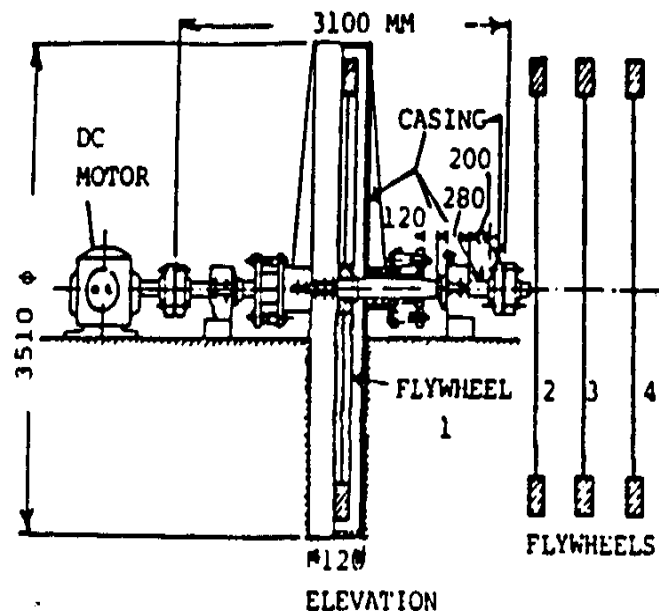have been developed (see Figure 1).

ues1x11.gif (600x600)

Figure 1. Flywheel Energy Storage System for a Solar Power Pack (10 Kilowatts--Electric)

Source: B.S. Magel and S.V. Jain, "Mechanical Energy Storage System for a 10 kWe Solar Power Pack," in Sun--Mankind's Future Source of Energy, eds. F. deWinter and M. Cox (New York, New York: Pergamon Press, 1978), p. 578.

Flywheels are small, but are high technology devices requiring sophisticated engineering know-how on the part of those who will

select the hardware and design the match to the wind or hydropower
installation. Once installed, semi-skilled operators can
maintain these installations under the supervision of an engineer.

III. COMPARISIONS AND RECOMMENDATIONS

Tables 5 and 6 give comparisons of the energy densities, conversion

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Table 5. Expected Technical and Cost Characteristics
of Selected Energy Storage Systems

Characteristics	Near Term					Intermediate Term			Long Term
	Hydro Pumped Storage	Compressed Air	Thermal		Lead-Acid Batteries	Advanced Batteries	Flywheel	Hydrogen Storage	Super Conducting Magnetic
			Steam	Oil					
Commercial Availability	Present	Present	Before 1985	Before 1985	Before 1985	1985-2000	1985-2000	1985-2000	Post 2000
Economic Plant Size (MWh or MW)	200-2000 MW	200-2000 MW	50-200 MW	50-200 MW	20-50 MWh	20-50 MWh	10-50 MWh	20-50 MW	Greater than 10,000 MWh
Power-Related Costs [a] ($/kW)	90-160	100-210	150-250	150-250	70-80	60-70	65-75	500-860	50-60
Storage-Related Costs [b] ($/kWh)	2-12	4-30	30-70	10-15	65-110	20-60	100-300	6-15	30-140 [c]
Expected Life (years)	50	20-25	25-30	25-30	5-10	10-20	20-25	10-25	20-30
Efficiency [d] (percent)	70-75	[e]	65-75	65-75	60-75	70-80	70-85	40-50	70-85
Construction Lead Time (years)	8-12	3-12	5-12[f]	5-12[f]	2-3	2-3	2-3	2-3	8-12

Source: Jensen, J., Energy Storage (London, England and Boston, Massachusetts, Newnes-Butterworths, 1980).

[a] In constant 1975 dollars; does not include cost of money during construction.
[b] Could be considerably higher.
[c] These numbers are very preliminary.
[d] Electric energy out to electric energy in, in percent.
[e] Heat rate of 4,200 to 5,500 Btu/kWh and compressed air pumping requirements from 0.58 to 0.80 kWh.
[f] Long lead time includes construction of main power plant.

efficiencies, state of technical development, cost data, and
potential applications of the various types of energy storage
systems. These comparisons, however, were based on data obtained

from large power plants, and therefore must be adjusted for small power plants.

The essential criteria for selecting an energy storage system are: (1) the technology should provide high conversion efficiency; (2) commercial hardware should be currently available; and (3) costs should be favorable compared to alternative options.

Based on the above criteria, the energy storage systems most likely to be both technically feasible and economical are:

1. Conversion to electricity via generators and storage in lead-acid batteries.

2. Storage as mechanical energy in a flywheel with recovery as mechanical energy.

3. Compressed air storage, combined with a turbogenerator for recovery of stored energy as electricity or as mechanical energy.

4. Pumped water combined with a turbogenerator for recovery of stored energy as electricity or as mechanical energy.

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