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Solar energy: battery energy storage control

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Abstract

A number of applications of battery energy storage in photovoltaic installations have been analyzed The use of lead/acid batteries enhances the efficiency and reduces the cost Some aspects of automatic charge/discharge control have been discussed The rate of variation of the battery voltage can be used to determine the state-of-charge This is based upon fundamental battery characteristics related to the kinetics of the lead/acid system Although the cost of solar cells is still quite high, photovoltaic energy systems are competitive, not only in small remote installations, but also in large industrial applications The wide range of working conditions necessitates precise evaluations of the solar array, but no particular problems appear to exist for the battery and the peripheral equipment

Introduction

This paper does not cover the complete details of photovoltaic electricity generation, but examines only the storage possibilities Lead/acid batteries are widely used for storage of electrical energy With photovoltaic-based supplies, there are some unique aspects with regard to the control of battery charging

Most solar power installations are in areas with a high incidence of sunshine. However, they are not always areas with a high population density In addition to meeting some of the existing energy needs, the solar systems may also provide energy for development, in particular for agricultural, industrial, and tourist activities It has been found that conventional hydroelectric or thermal power stations sited in remote regions are not as efficient as those in industrialized centres The high cost of both the construction and the distribution network is not justified for the relatively small amount of energy consumed locally It might be more attractive to have smaller electricity generators and augment these with independent solar generators Furthermore, photovoltaics with battery storage offer a practically maintenance-free and absolutely pollution-free system These aspects are presenting more and more difficulties for conventional and nuclear power plants

Due to the high cost of photovoltaic generators, the efficiency of the consumption of solar energy is of great importance Of course, the use of more energy-efficient devices is also attractive in conventional power systems, but the higher cost of investment has to compete with the relatively low energy cost

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Solar energy has to be consumed locally in order to avoid conversion and distribution losses The installation of large solar systems feeding into an a c distribution network is of limited interest Virtually no savings are possible in the electricity generating equipment This approach is chosen to avoid the installation of a storage system Electricity utilities have an interest in storing energy to meet the peak-power requirements The great interest in load-levelling systems, using lead/acid batteries for energy storage, has already resulted in several very large storage units

Solar energy is certainly very attractive for load-levelling applications The combination of a pollution-free, battery energy storage system and a 'clean' photovoltaic energy supply results in an efficient peak-power supply without harmful environmental effects At the same time, the economics are greatly improved as the expensive solar energy is used to supply electricity at peak-power rates

The same advantages are present in small, stand-alone installations The energy consumption is not synchronized with the solar radiation The use of battery storage enables the use of smaller photovoltaic generators as the consumption peaks are levelled out by the battery The larger the battery, the less a diesel-generator will have to be operated In certain cases, a primary battery, e g , aluminium/air, may be used as an emergency power supply Reliability and flexibility are intrinsic characteristics of electrochemical energy storage

The electrical features of a solar generator have to be taken into account when charging the battery The particular requirements for both the charge and the operation of the lead/acid battery must be considered in order to obtain the most efficient, i e , the most economic, use of solar energy This requires an extensive investigation for each application An optimal system configuration will present the closest match between generator, storage, and user It might be necessary, however, to provide a certain flexibility to cope with future requirements and with improved technologies

As the various applications and sites are widely different, only general outlines will be presented and, in particular, no reference to existing electrical equipment is made in this paper

Advantages of battery energy storage

Figure 1 presents a general diagram of a photovoltaic energy supply The energy flow varies for each application and this has to be established prior to the determination of the size of the equipment

The use of a storage battery reduces the energy efficiency through electrical and electrochemical losses, but allows the use of a smaller generator and provides energy when it is required A further reduction in the size of the solar panel is possible by giving priority to the charge of the battery

Before discussing the battery charge aspects, it is first necessary to understand the practical use of solar energy

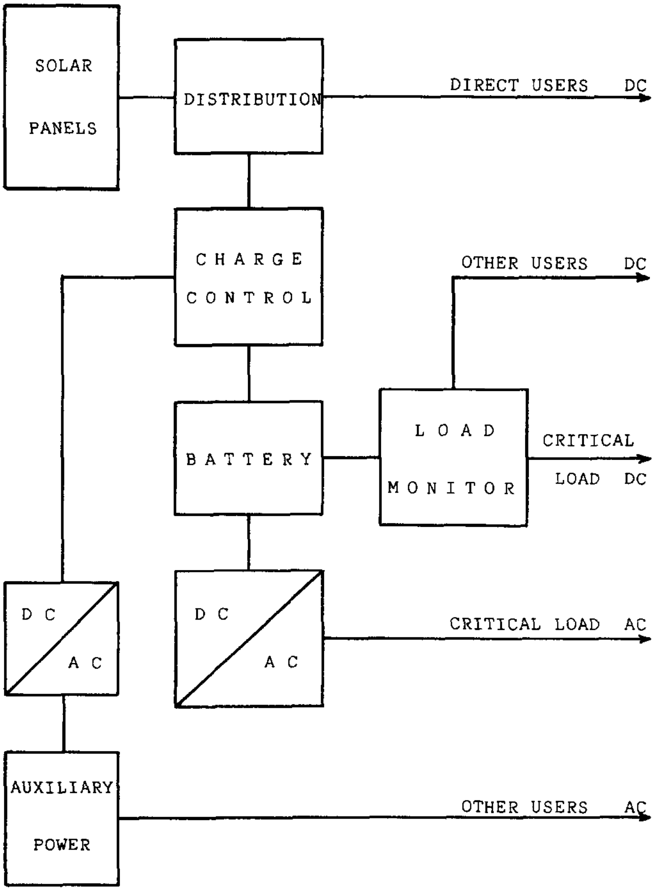

Fig 1 Photovoltaic energy supply

Examples of battery storage in solar energy systems

(i) The first example, showing the effect of battery storage, is for an agricultural community The following system parameters are assumed
power for pumps, irrigation, etc 3000 W, operation 6–10 h/day
power for household applications 2000 W, operation 8–14 h/day
direct use of solar energy 18–30 kW h/day
energy to recharge the battery (1.3 × consumption) 20–36 kW h/day
required autonomy 3–5 days

To avoid overdischarging the battery and to maintain sufficient energy for a critical load, the battery size has to be 100–240 kW h

The solar panel has to supply the direct load – 3000 W – and the energy to recharge the battery The required maximum power output is 8 kW, and at an average efficiency of 60%, the installed power will be 13 kW

The investment is as follows (prices are OEM, without installation)

solar panel 13 kW$_p$ at \$ 5/W$_p$	\$ 65 000
battery, ~200 kW h at \$80/kW h	\$ 16 000
charge regulation, load control	\$ 3 000
Total investment	\$ 84 000

No provision is made for interest, and an amortization period of only six years is taken The annual costs are \$ 14 000, i e , \$ 40/day for a power of ~5 kW and an energy of ~40 kW h After six years, only the cost of the battery replacement has to be taken into account, i e , ~\$ 5/day

The result does not change if seasonal variation in load is taken into account, i e ,

Summer	pumps, etc , 8 h×3000 W	⟶ 24 kW h	45 kW h/day
	households 8 h×2000 W (×1 3)	⟶ 1 3×16 kW h	
Winter	pumps, etc , 4 h×2000 W	⟶ 8 kW h	45 kW h/day
	households 14 h×2000 W (×1 3)	⟶ 1 3×28 kW h	

maximum output of the solar array 10 kW

smallest size of battery storage 100 kW h ⟶ charge rate $i = 0\ 1$ C
largest size of battery storage 250 kW h ⟶ charge rate $i = 0\ 04$ C

minimum useful output of the solar panel 2 kW

smallest size of battery storage 100 kW h ⟶ charge rate $i = 0\ 02$ C
largest size of battery storage 250 kW h ⟶ charge rate $i = 0\ 008$ C

Thus, the duration for the total recharge of the battery is from some 3 h up to about one month These times are acceptable for a lead/acid battery For this particular application, with the battery used daily, a larger battery (e.g , >250 kW h) will not offer a better protection as the recharge will become insufficient

The fairly large solar generator of 13 kW$_p$ will provide a high excess of energy that cannot be stored in the summer months A smaller photovoltaic system, 8 kW$_p$, supplies sufficient energy in the summer, but requires the use of a diesel generator (3 kV A) for balance in the winter In this case, a much smaller battery can be used The installation and operating costs of this equipment over a six-year period will be

solar panel, 8 kW$_p$ at \$5/W$_p$	\$ 40 000
battery, 60 kW h at \$ 80/kW h	\$ 5 000
diesel generator	\$ 2 800
maintenance diesel, 100 h/yr at \$ 30	\$ 18 000
fuel, 8 h/day, 100 days/yr at 0 5 l/h and \$ 0 30/l	\$ 700
charge regulation, load control	\$ 3 500
Total costs	\$ 72 000

After this period of six years the operating costs remain very high, namely, ~$ 5000/year. So, the cost of the power (kW) and of the energy (kW h) are not any different from the installation without a diesel generator Moreover, the photovoltaic-only system is pollution-free, noiseless, and reliable The diesel generator substantially shortens the recharge of the battery, with a typical average rate of 0.02 *C*, but uses the same charge regulating system as for the solar energy.

(ii) A further interesting application of photovoltaic/battery systems is street lighting or a similar application with only indirect utilization of solar energy

Total power 2 kW

Storage required, in winter, 14 h, reserve 5 days 5×14×2=140 kW h

Investment:

size of battery, 200 kW h at $ 75	$ 15 000
solar panels, 6 $\mathrm{kW_p}$ at $ 5/$\mathrm{W_p}$	$ 30 000
charge regulation, load control	$ 3 000
Total investment	$ 48 000

In summer, there will be excess energy, i e ,

solar panels provide	32 kW h
lighting takes	16 kW h
excess	16 kW h/day

This is sufficient for pumping, irrigation, tourism

Optionally, an additional storage of 100 kW h can be installed

additional investment	$ 8 000
total investment	$ 56 000

Total amount of energy provided 8000 kW h+4000 kE h=12 000 kW h/yr

Life of the installation. 12 years, thus cost of energy: $0 40/kW h

The charge rates are similar to the ones mentioned above.

A comparison with a diesel generator power supply gives·

generator $ 3000, life 6 years.

Fuel: 365 days at 11 h at 0.5 l/h=2000 l at $ 0 60=$ 1200

Total cost over a period of 12 years

2 generators	$ 6 000
fuel 12×$ 1200	$ 14 400
maintenance: 12×$ 3000	$ 36 000
Total operating costs	$ 56 400

Clearly, the solar energy system is to be preferred.

(iii) A third example of the use of solar energy is in warning lights A very simple system consists of a solar panel (5 $\mathrm{W_p}$), a battery ($\geqslant$120 W h), and a flashing light (5 W, on· 0 5 s/off: 1.5 s).

The energy storage system can be a sealed lead/acid battery, either 6 V, 24 A h or 12 V, 15 A h The total cost of one module (mass production) is about $ 100 Service life may be estimated at 3 years The reliability is similar to that of a warning device powered by a primary zinc/air battery, life 8–12 months

The low power output of the solar panel does not present any risk of overcharging the battery Rather, the difficulty lies in the probability of a low state-of-charge (SOC) over an extended period So the accent, as in the examples above, is on monitoring the battery SOC

Battery aspects

For the three examples above, the following summary may be developed

$$\text{ratio battery} - \text{load} \quad \left.\begin{array}{l}\text{(a) } 200 \text{ kW h} - 2 \text{ kW}\\ \text{(b) } 200 \text{ kW h} - 2 \text{ kW}\\ \text{(c) } 150 \text{ W h} - 1\ 3 \text{ W}\end{array}\right\} \text{discharge rate } 0\ 01\ C$$

$$\text{ratio battery} - \text{charge} \quad \left.\begin{array}{l}\text{(a) } 200 \text{ kW h} - 2/10 \text{ kW}\\ \text{(b) } 200 \text{ kW h} - 1/5 \text{ kW}\\ \text{(c) } 150 \text{ W h} - 4 \text{ W}\end{array}\right\} \text{charge rate } 0\ 1\text{–}0\ 01\ C$$

Several lead/acid battery types are currently available

(i) vented cells with excess electrolyte of low density,
(ii) vented cells with standard quantity of electrolyte at moderate density,
(iii) sealed cells with limited amount of electrolyte at higher density

Preferential system voltages are 12, 24, 48, 120 or 220 V d c

Preferential battery capacities are between 100 and 400 A h

It is not possible to consider in detail the various combinations of the voltages of the solar array, the storage battery, and the consumers Solar panels are, more or less, standardized at 16 V, 50 W The battery and user circuits are more efficient at higher voltages

Several parameters have to be taken into account for the final lay-out of the system Figure 2 presents a possible architecture The series and parallel connections are designed to increase the reliability of the system Furthermore, it is important to monitor the system's performance and to detect faults A high uniformity, i e , good quality, of solar cells and battery modules is fundamental for maintenance-free operation and the highest possible energy output Uniformity can be measured by the current flow at the points 's' (Fig 2) In general, the actual value is of less importance than the deviation in a particular string All these precautions are necessary to ensure an efficient use of the current At low charge rates, even a small loss will lead to an insufficiently charged battery

Figure 3(a) and (b) presents typical current–voltage characteristics of solar cells The charge and discharge voltage curves for a lead/acid battery are shown in Fig 4

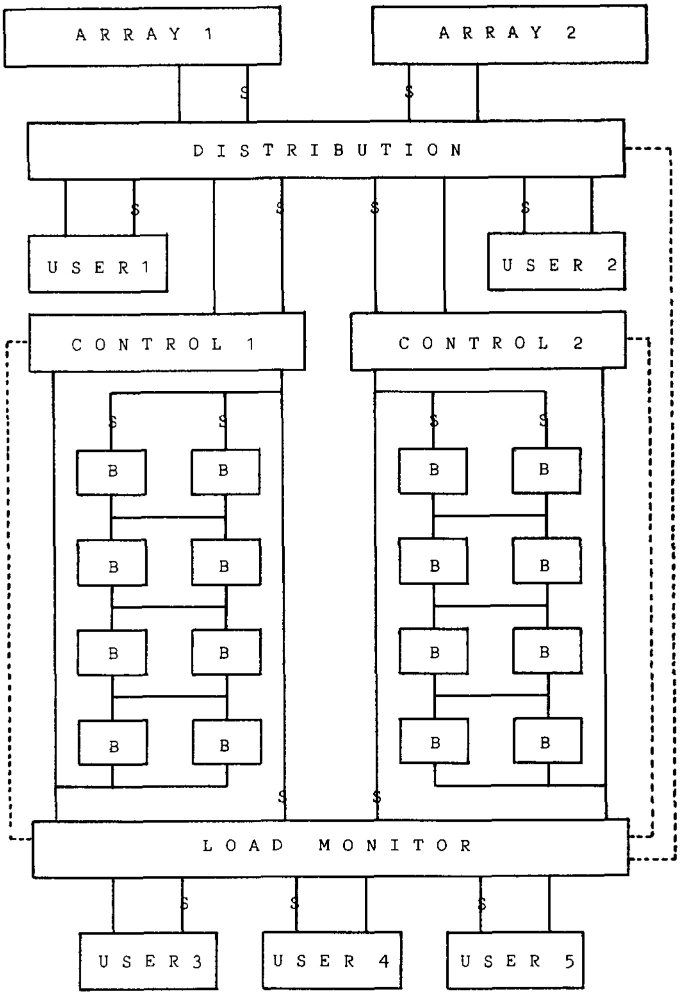

Fig 2 Solar energy power supply

A special d c –d c converter, a so-called 'power tracker', accommodates the voltage variations (Fig 5) The input adjusts automatically to the maximum power output of the solar panel The converter output will provide maximum power to the user, either directly or for charging the battery The efficiency of the power tracker is very high, ~ 97%, through the use of high frequency, transistorized, transformerless circuitry

The battery charge control unit has two functions· (i) regulating the charge, (ii) limiting the discharge In the example given in Fig. 2 there are two battery circuits, this arrangement greatly increases the flexibility The control unit is capable of switching off certain non-critical loads, to maintain one set of batteries at a higher SOC, and to provide reserve energy for long

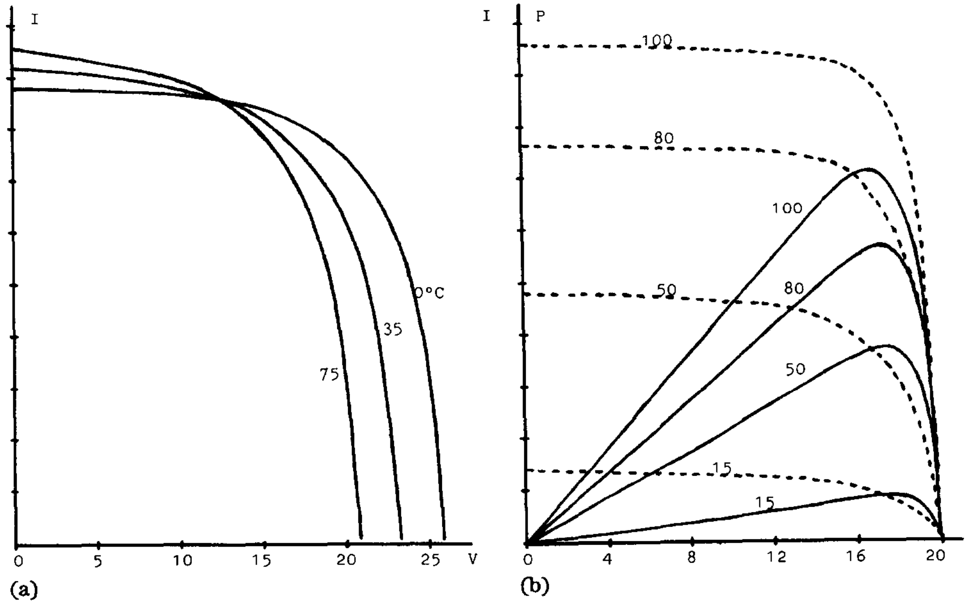

Fig 3 (a) Current/voltage characteristics of solar cells, (b) power output of solar cells

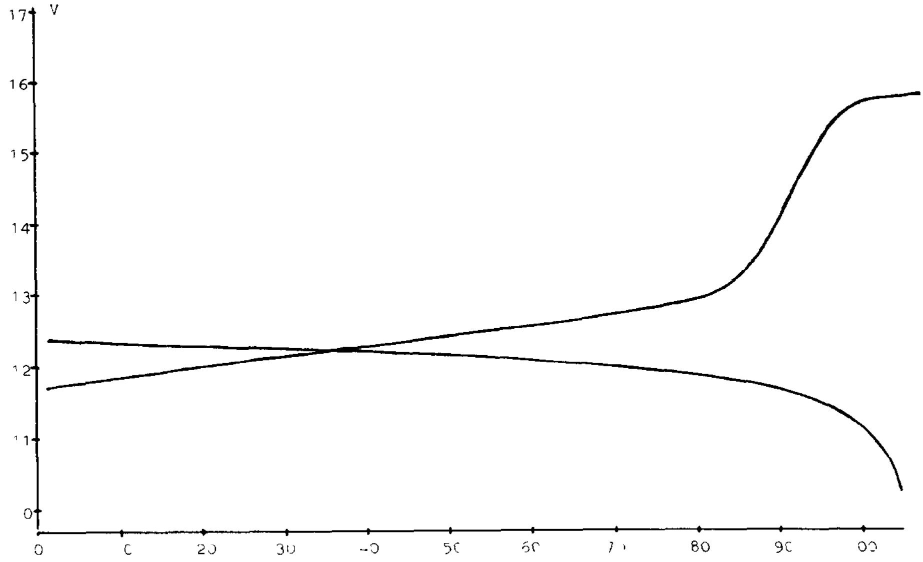

Fig 4 Voltage characteristics of lead/acid batteries

periods in the absence of sun. Power-saving units are widely in use in a.c circuits to limit peak power consumption. From this, it follows that not only the wide variations of the output of the photovoltaic generator, but also the variations in battery charge current and in battery discharge require an 'intelligent' control unit. Any attempt to calculate the energy flow by current

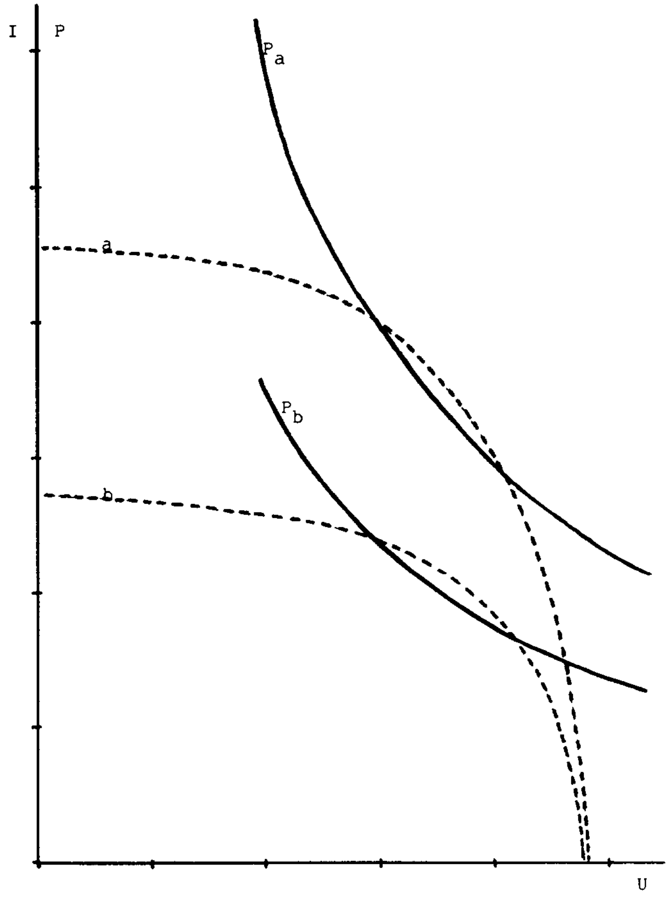

Fig 5 Principle of maximum power tracker

integration is likely to fail The information on the SOC has to be provided by the battery itself

From the data given in Fig 4, it can be seen that the variation of the battery voltage at nearly full charge may provide information It is very difficult, however, to foresee the end of discharge, particularly as the depth-of-discharge (DOD) has to be limited Figure 6 shows the variation of battery voltage for four situations no load (open-circuit voltage, OCV), small load, and increased loads These curves indicate the difficulty of defining an end-of-discharge voltage Nevertheless, the SOC may be derived using the ratio $\Delta U/\Delta i$, as presented in Fig 7

A particular property of lead/acid batteries, and of solar cells as well, is the temperature coefficient Whereas the performance of solar cells decreases at higher temperatures, the battery output is higher This has to be taken into account to determine the actual size of the installation The use of a power tracker simplifies the temperature corrections, but it does not affect

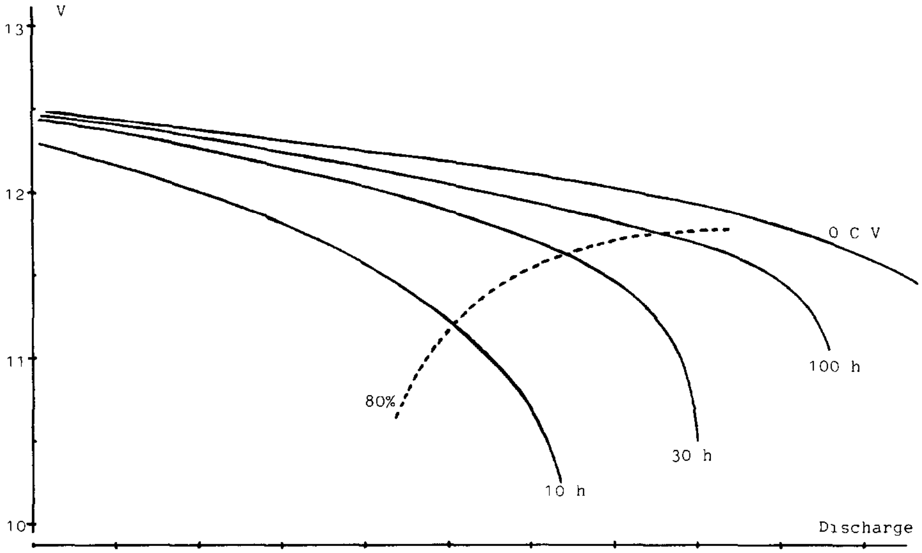

Fig 6 Battery voltage under various loads

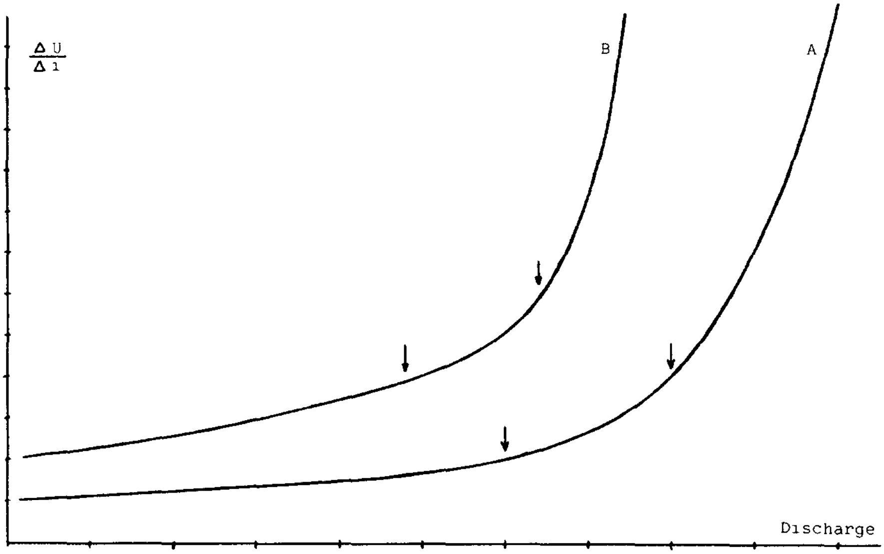

Fig 7 Variation of battery discharge voltage, $\Delta U/\Delta i$

the actual battery charge or discharge voltage, which still varies strongly with temperature For this particular reason, the use of the derivative $\delta U/\delta t$ is very attractive, although the slope, too, depends on temperature

Going one step further may provide a possible solution, i e , using the rate of variation to control the charge of the battery or to monitor its SOC

This is logical as the electrochemical processes of the lead/acid battery are controlled by concentration gradients

Attempts have been made to formulate an analogous electrical circuit for the lead/acid battery For the electrical engineer this is an obvious solution, and by adding sufficient boundary conditions some kind of algorithm may be developed Based upon practical data for a particular type of battery, this empirical approach gives correct results for a limited range of applications The greatest difficulty is to accommodate the ageing characteristics and the increasing deviation from the standard value

The electrochemical processes of the lead/acid battery are fairly well understood, and accurate formulae to describe the charge and discharge reactions have been developed These are helpful in the design of batteries and some models, particularly the 3D-types, are very precise Unfortunately, these calculations require large computing facilities It is to be expected, in the near future, that an interactive program, using bi-directional current flow, will provide full information on the SOC

Current regulation is an important aspect, as this leads to fast, efficient recharge and to limitation of the DOD The variation of the typical charge and discharge voltage characteristics of the lead/acid battery, as shown in Fig 4, is presented in Fig 8 This derivative illustrates more clearly the concentration gradients that exist within the battery The dynamics of the battery activity can be found by looking at the kinetics, i e , the rate of variation This is shown in Fig 9 A great advantage of this presentation is that only fundamental battery characteristics are considered The particular construction of the type of battery has very little effect Using the rate of variation of the battery voltage eliminates the dependence of the voltage

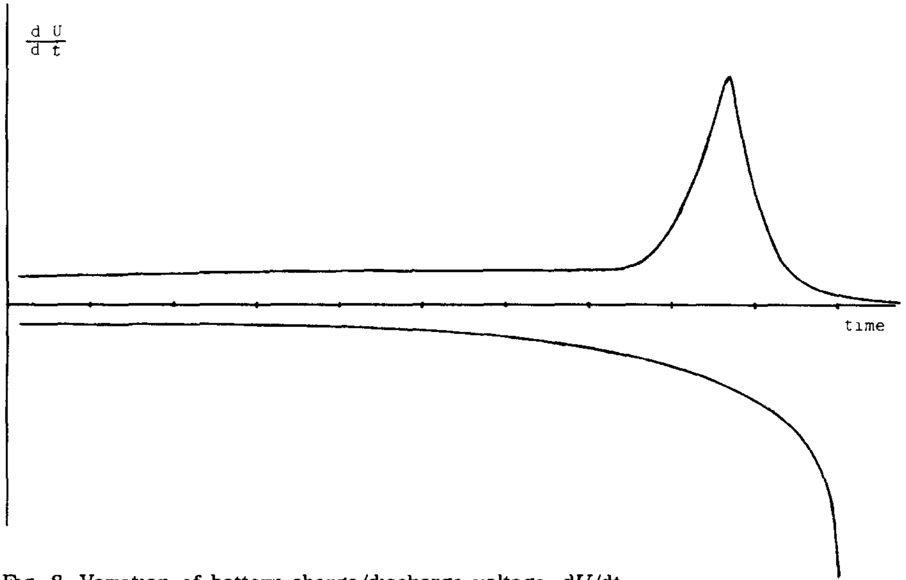

Fig 8 Variation of battery charge/discharge voltage, dU/dt

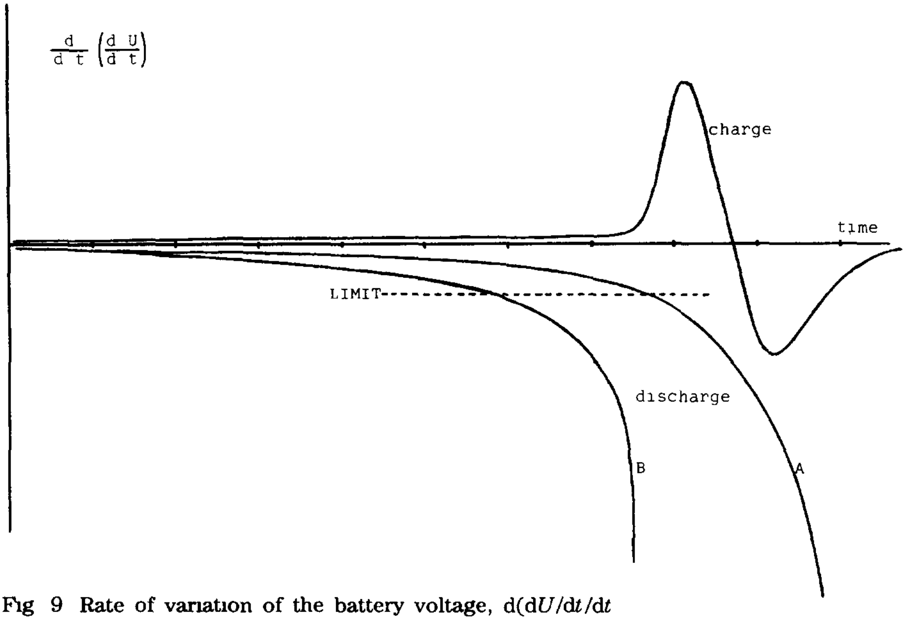

Fig 9 Rate of variation of the battery voltage, d(dU/dt/dt

level on temperature, acid density, age, etc The amplitude and slope follow the SOC of the battery To a certain extent these values may be used to check the state of health of the battery, but this is not the primary objective of this discussion

The regulation method

The above analysis provides a fundamental base for the control of battery charge and discharge and for the matching of the current flow with the kinetics of the electrochemical reactions An enormous advantage is the reduction of the amount of information and, combined with the slowness of the battery operation, particularly in solar energy storage applications, the necessary control circuit is extremely simple There are two approaches analog or numerical control

An analog circuit is simple and inexpensive and it offers good control possibilities for a large number of applications, particularly in the motive power field Much care is required, however, for the stability and the protection circuits

The digital approach offers nearly unlimited scope The advent of inexpensive microprocessors not only gives storage possibilities for long-term operation, but enables the control of several strings of batteries and solar cells with only one unit Evaluation of the energy flow is possible, as well as monitoring of the battery SOC. The higher cost, especially for the development, is a drawback because, at present, no mass production exists Moreover, in order to achieve high reliability, several independent watchdog circuits are necessary The unattended operation also requires reset circuits and remote warning devices

Figure 10 shows some of the operational characteristics

- load-shedding, in order to save energy for more-critical loads
- limiting of the depth-of-discharge, to avoid overdischarge
- switching off of primary circuits to increase the recharge
- searching for disparities in current distribution, both in the solar panel and in the battery strings
- presenting an energy balance for the system with, if required, the amount of energy consumed by each user circuit (billing)
- monitoring the system's status in an easily understood way (e g., red and green lights)

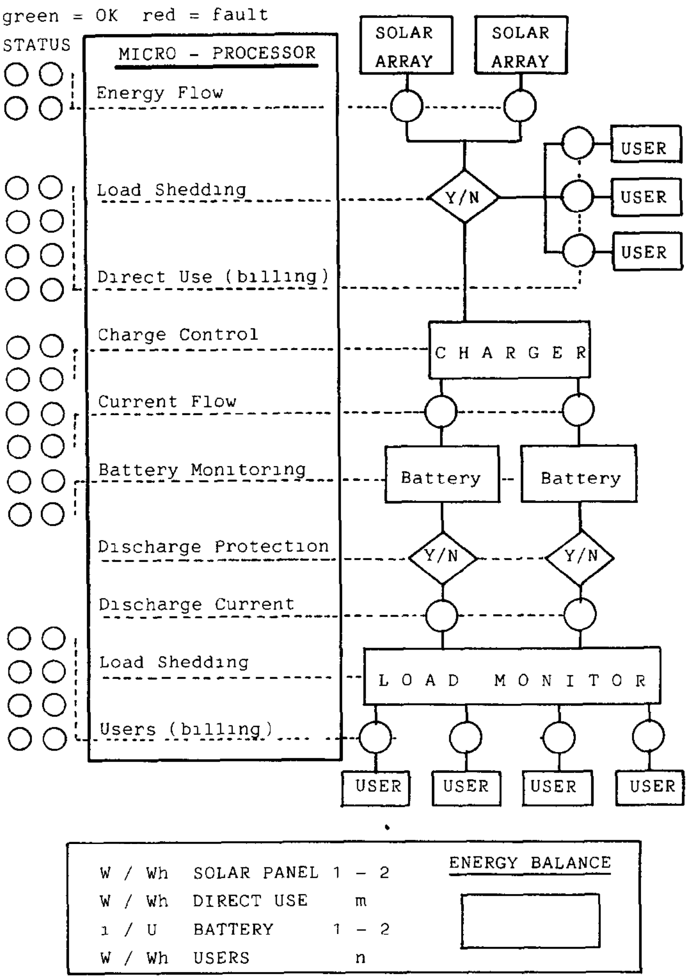

Fig 10 Regulation method of solar energy supply

- controlling the battery charge current to avoid unnecessary overcharge, but still maintaining the highest possible charge rates.

The last operation uses the power tracker for independent energy conversion to ensure the fastest possible recharge. Decreasing the charge current can be achieved by adjusting the operational point of this converter or, more simply, by decreasing the number of solar cells, i.e., reducing the primary energy input. This reduces the power handling capability of the power tracker and limits the heat dissipation problem.

Here the advantage of using the rate of variation of the battery voltage is decisive, as neither the charge current nor the SOC are constant at any time. Variations in sunshine provoke charge and discharge of the battery. This is a specific feature of solar energy systems. The charge is not progressive and the SOC increases and decreases. Fortunately, the charge and discharge currents are fairly low, so the variations may be integrated over a long period.

The controller may recognize the status by measuring the voltage variation only, as shown in Fig. 8. To avoid a premature capacity loss by operation in a low SOC, the controller will give priority to the recharge as controlled by the rate of variation. The controller, through its load shedding capability, promotes a high SOC. The increased readiness of the battery is the best way of assuring an efficient use of solar energy. Automatically this compensates for any malfunctioning, either in the solar panel or in the battery strings. The objective is a reliable power supply, even in fully unattended operation.

Maintaining a high SOC increases the life of the battery and the available capacity. The actual type of battery is not of great importance, as long as the cells are of high uniformity. The final choice depends on the cost, the volume and weight, and the available low-rate capacity (sealed batteries are generally tailored for high-rate applications).

It should be pointed out that the operation of a lead/acid battery in a solar energy system is considerably different from usual applications, where the battery is recharged from the mains supply. In the latter, the charge current is much higher and continuously available at low cost. An elaborate current–voltage profile may be programmed for fast and efficient recharge, assuring excellent cycle life. In stationary applications a very long charge time is available and a constant voltage recharge is an acceptable solution.

By contrast, in solar energy systems the charge current is varying continuously with the insolation level, and, at the same time, energy will be consumed by the direct users. This excludes the use of a particular voltage–current programme. Moreover, the battery has to be recharged frequently (normally each day) and as quickly as possible. This excludes the use of a constant-voltage charge. Finally, even during the charge period (i.e., in daytime) a partial discharge may occur.

The charge and discharge currents are constant neither in amplitude nor in time. The interpretation of the voltage fluctuations requires a very complicated algorithm to match a ‘reference’ curve. These fluctuations also show up in the derivatives, and increase and decrease the battery SOC. The variations in charge/discharge current have to be memorized, particularly when nearing full SOC

The battery can indicate its status by the kinetics the rate of variation of the voltage depends on the rate of the reactions, i e , on the concentration gradients

Realization of the regulation

In conventional battery applications, with separate charge and discharge operations, a control circuit using $\mathrm{d}U/\mathrm{d}t$ can be realized by current switching The charge duration is no longer as sufficient power is available These units are particularly useful for high charge rates and quite insensitive to the battery temperature

In solar energy storage systems, a relatively-long sampling period may be used, e g , 15 min The regulation circuit compares the variation over each sampling period with the previous value If the variation of the voltage is positive and higher than the previous variation, the battery still accepts the charge current and no power reduction is required If the variation is positive, but smaller than the previous variation, the battery is nearing its full SOC and the current will be reduced If the voltage does not vary, the battery is in a stable condition and no further charge is required If the voltage variation is negative, the battery is being discharged If the variation is increasing, the battery is nearing its end of discharge

The actual amplitude of the variations and the number of periods, or the length of each measuring period, depend on the charge/discharge rate It is possible to determine the SOC by measuring, during a discharge period, the voltage variation at a certain discharge current (see Fig 7), e g , by switching on a fixed load for a few seconds every 15 min or so The value of $\mathrm{d}U/\mathrm{d}t$ can then be used to limit the discharge, e g , by reducing the load

As $\mathrm{d}U/\mathrm{d}t$ depends on the temperature, this automatically compensates for the capacity reduction at lower temperature, and effectively protects the battery against overdischarge This is extremely important at the low discharge rates found in solar applications The DOD is an important parameter at low charge rates the greater the DOD, the more difficult and less efficient will be the recharge

The value of $\mathrm{d}U/\mathrm{d}t$, also called the 'internal resistance', varies with the type of battery and a number of other parameters The rate of variation is, however, indicative of the SOC As long as the rate is constant, the battery can cope with the load If the rate increases, priority may be given to the recharge, e g , by reducing the consumption of the direct users Normally, this will be effected on a 24 h basis For particular applications, especially if two battery strings are present, one battery may be brought to an increased SOC

A good method of control is integration of the charge current This battery will stay on charge until at least 50% of the nominal capacity has been returned This situation will generally prevail in the winter period The solar array must be oriented to give the maximum power output when the period of sunshine is short In example (i), above, it was seen that the variation of the seasonal load requires the highest amount of stored energy in the winter period This has to be taken into consideration when sizing and installing the solar array The battery has already been designed for the required autonomy and the ratio in example (i) is

installed peak power of the solar array 13 kW
maximum size of the storage battery 200–250 kW h

It was shown that the use of a smaller array, 8 kW_p, is not more economical, whereas a larger array will become too expensive

The above models are, however, not typical, they are only examples for calculating purposes The loads will have to be determined for each application But, essentially, the same pattern will be encountered as outlined here Therefore, the same charge problems will be encountered and the charge-regulation method will apply to most installations

Other charge control techniques

There is not much to be said about the various charge regulation systems in use For the limited number of applications of solar energy with battery storage in large systems special surveillance circuits are in use The presence of auxiliary generators simplifies the charge, but these offer no technical or economic advantages

More widely in use are small systems, particularly in places where the cost of connection to a mains supply is too high for the small amount of energy consumed locally The average power of the solar panel is so small that no charge regulation is required The current–voltage characteristics of solar cells automatically reduce the charge current when the battery nears full SOC and its voltage increases The size and economics of these installations cannot be compared with an industrial application, although the overall performance, particularly for telecommunications, is extremely satisfactory

A very large number of photovoltaic generators supply direct loads only, mainly for water pumps These typical, small rural applications may offer possibilities for the improved use of electrical energy The first step would be the addition of a battery to store the excess energy, which can be used to improve the living conditions Of particular interest is the replacement of dangerous (fire) oil lamps and the provision of cooling for perishable products Here, the modular construction of solar panels and batteries is a distinct advantage, compared with the high cost of adapting a distribution network An energy-supply system for an agricultural community, e g , example (i) above, may grow from a small installation If only a small amount of solar energy is to be stored, little charge control is required, but efficiency and reliability are not guaranteed

An important aspect of the growth possibilities is the engineering involved As practically no trained electricians are usually available locally, the equipment has to be safe and maintenance-free The cost of preparation, however, seriously affects the price of the equipment, as the time and travel of engineers has to be paid for, one way or another Therefore, local intervention must be eliminated This means that an appropriate control system has to be installed even for a fairly small power supply Additional costs arise from the availability and compatibility of the installation material Training of local contractors offers an attractive solution This may be integrated into local education programmes without affecting the financing of solar energy equipment Little detailed information on charge control is available in the literature

Constant-voltage charge

This charge method is used in installations with very limited DOD and low-power charge rates Temperature compensation should be applied This is a low-cost solution and is not very energy efficient It may reduce battery life, especially because cheap automative batteries are often employed For these installations, batteries with thick plates and a large excess of electrolyte are recommended

Constant-current charge

As solar batteries are cycled, the obvious solution is to adopt a charge method of the type used for motive-power cells The limited power availability may present some problems for charge control A comparison of the characteristic power (W) curve and the voltage/current profile of solar cells is given in Fig. 11 The use of current integration should allow full recharge, with limited overcharge Attention should be paid to electrolyte stratification, particularly if tall cells are employed

A reconditioning charge, every few months and/or after a deep discharge, assures excellent battery life With only one system, i e , one solar panel array and one battery string, the equipment is, generally, very much oversized in order to meet the winter situation These installations are still very much cost-effective for unattended operation

The relatively small size of this type of installation does not justify the use of a power tracker and an array with a higher voltage is used Series regulation assures current/voltage control This allows the use of sealed batteries Such units are very attractive for remote, often inaccessible, installations The main concern is the maintenance of the solar panels

d c -d c converters

Solid-state converters greatly enhance the power and energy efficiency of solar systems The use of high-frequency switching circuitry and low impedance MOS-FET devices assure reliability and efficiency As more energy at a low insolation level becomes available, either for direct use or for storage in the battery, a smaller array may be used

The efficiency of the charge is improved as a higher voltage may be applied, even at low insolation levels This is of great importance for those installations operating under unfavourable climatic conditions

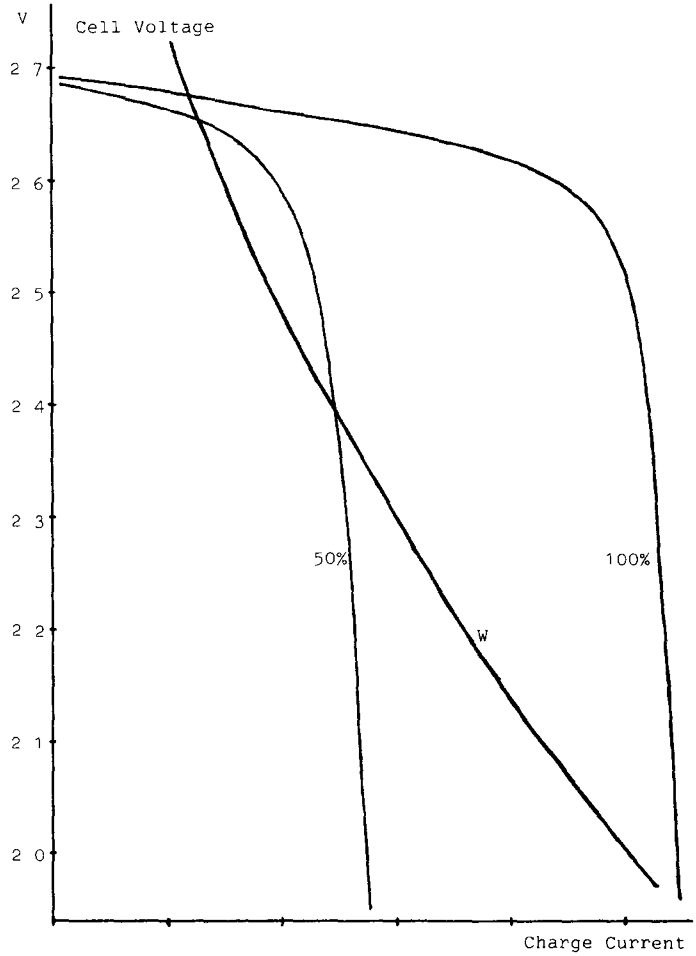

Fig 11 Charge W vs voltage/current of solar cells

d c –d c converters are available in all sizes, voltages, and power, and can be set for constant-current or constant-voltage operation In a typical charge mode, the converter may be switched on and off at preset battery voltages. An additional advantage for direct use is a narrower voltage range, providing protection at high insolation levels and, thereby, extending the life of the equipment

Maximum power tracker

This extension of the d c –d c converter increases the power efficiency of the solar array In general, it offers a wider input-voltage range than standard d c –d c converters If the equipment is sized for operation in the winter period, then the excess voltage in summer can be reduced by switching out some cells in the array This energy loss is of no great importance as it cannot be used *d c.–a.c converter*

The conversion of solar energy to an a c voltage must be limited to the use of necessary equipment The low energy efficiency of most a c equipment is the main reason to avoid d c to a c conversion

If a c conversion is necessary, the converter should be connected to the battery and be of the transformerless type The use of a d c –a c converter for a battery charger or for feeding into the mains supply is very inefficient, even if the d c converter is of the switching type

An attractive proposition is the supply of peak power, i e , using solar energy storage if the cost of additional peak power is very high The amount of possible solar energy in industrialized areas is only a few percent of the total energy consumption Nevertheless, storage for peak power will increase this ratio and may substantially decrease, or eliminate, the cost of additional peak-power generation equipment The annual variation in sunshine is the limiting factor

The energy requirement for cooling and air-conditioning increases with the amount of sunshine. So, logically, more cooling is required in those areas with more sunshine Therefore, solar energy would be an attractive energy supply, especially as it is both pollution and maintenance free As with other load levelling applications, the size of the battery is determined by the maximum daily need and no extended autonomy is required Also, the maximum available solar energy is effectively used This gives an improved energy efficiency and results in a smaller array and lower investment costs

A well-oriented array of 10 $\mathrm{kW_p}$, with a storage battery of 100 kW h, will provide 30 kW for 1–2 h. The investment is:

solar array, 10 $\mathrm{kW_p}$ at \$ 5/$\mathrm{W_p}$	\$ 50 000
installation	\$ 12 000
battery, 100 kW h at \$ 80/kW h	\$ 8 000
charge control–load monitor	\$ 4 000
converter, 30 kV A	\$ 20 000
various, engineering, etc	\$ 8 000
Total investment	\$ 102 000

This equipment can be used as an emergency power supply, value \$ 32 000, which we may deduct from the budget Thus,

Net cost of this installation: \$ 70 000

Amortization over a period of 20 years

amortization	\$ 3 500
interest, average 5 5%	\$ 3 850
maintenance, repairs, etc.	\$ 2 650
Annual operating costs	\$ 10 000

monthly peak-power demand charge $ 20/kV A
operation 8 months/year at 30 kV A peak power
annual savings in the electricity bill $8\times30\times20=\$\,4800$
energy savings 200 days at 1 5 h at 30 kV A at $ 0 12/kW h = $ 1200

Total annual economy $ 6 000

This analysis shows that the cost of solar power is not competitive The main reason is the high cost of the solar panels In addition, the interest rate represents another heavy burden For break-even, over a 20-year period, the cost of solar cells (including installation) should not exceed $\$\,3/\mathrm{W}_\mathrm{p}$ while the interest rate for this type of installation should not exceed 8%

The initial investment is much higher than for thermal generators, gas turbine, or diesel, but the low operating costs, noise-free operation, total absence of pollution, and the reliability are distinct advantages with solar energy storage systems

As in other load-levelling facilities, a monitor unit is required to switch the main users to the battery supply This is a particular situation where a mains circuit exists and advantage is taken of the tariff structure The charge control is simple, as the total energy flows over a 24-h period and only the air-conditioning equipment is supplied by the battery No current regulation is required The charge is continuous till some 102–106% of the discharged A h have been recharged, when the current will be interrupted Charge equalization can also be accomplished by current switching

The whole system could be provided as a standard package This would reduce engineering and development costs A modular configuration will satisfy the requirements of a small, individual installation and provide the possibility of expansion for large industrial systems

It is interesting to note that the solar panels can be cooled, and can be part of a heat-exchange circuit for the production of warm water This hybrid configuration is, however, not a standard version