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Appropriate battery technology for a new, rechargeable, micro-solar lantern

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Abstract

A detailed market survey in Kenya has assessed the performance of currently available domestic lighting systems, for example, kerosene 'hurricane' lamps and (generally poorly constructed) solar lanterns, against end-user expectations. Following this survey, the UK Government's Department for International Development approved a project to design and develop an affordable, reliable and efficient solar lantern, which would provide improved lighting to rural households. This paper provides an overview of the end-user requirements, and corresponding lantern design features. The suitability of three commercially available alternative battery technologies, viz., nickel – metal-hydride, nickel – cadmium, and valve-regulated lead – acid (VRLA), for use in this PV application are discussed. Finally, improvements to the VRLA batteries are proposed, which would further enhance their cycle-life and reduce the energy cost per cycle.

Keywords: Household lighting; Photovoltaic power-supply systems; Remote areas; Valve-regulated lead – acid batteries

1. Introduction

It is well established that often, limited power-generation capability, together with associated ageing and/or fragile distribution network – particularly in developing countries – leaves vast tracts of the country, and the households within these regions, without mains-electricity. This is particularly evident in Kenya, for example, where approximately 700 MW of generating capacity is distributed via the national grid to about three million people, or roughly 10% of the population. Despite ignoring the demands of the industrial sector, this means that each private user has access to only a meagre 200 W, and even these fortunate few are subjected to frequent brownouts, as the system fails to cope with the ever-increasing demand and/or with the inadequate power-distribution infrastructure.

With suitable (low-cost) amorphous silicon photovoltaic (PV) modules, and appropriate energy-storage batteries, alternative supply systems offer a viable source of electrical power to the frequently remote, off-grid user. Typical examples of the successful implementation of solar energy include; telecommunications and navigation systems, remote power supplies for cathodic protection, vaccine refrigerators in remote health centres and, increasingly, small d.c. domestic lighting systems. In all these applications, battery selection is often a trade-off between price and the desired performance (i.e., energy-storage capacity and cycle-life).

Intermediate Technology Consultants (ITC) have designed a new, rechargeable, PV (or solar) lantern, which will provide affordable, reliable, and improved lighting to rural and peri-urban households in the developing countries (e.g., Brazil, Kenya and India) where there is a clearly defined need for more domestic lighting systems. ITC is a wholly owned subsidiary of the Intermediate Technology Development Group (ITDG) with offices in Bangladesh, Kenya, Nepal, Peru, Sri Lanka, Sudan and Zimbabwe.

This project has been funded by the UK's Department for International Development (DFID), which is responsible for promoting social and economic development, and for reducing poverty. DFID is committed to the internationally agreed target of halving the proportion of people living in extreme poverty by the year 2015 [1].

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2. End-user expectations

The demographic profile and market potential of Kenya was studied, and an initial market review identified the following segments (in order of priority) for the low cost, solar lantern;

- rural households,
- urban households,
- rural small businesses,
- tourism,
- non-government organizations/relief/church-funded schemes,
- government.

Of these, the requirements of the rural 'environment' of households and small businesses (where there is greater need for a low-cost, effective and reliable lighting systems) were assessed. The results of the market survey with respect to the end-user expectations of these sectors are summarized in Table 1 [2]. The survey identified four critical product features that should be improved in the design of a new solar lantern, namely:

- light duration should be increased to between 3 and 4 h;
- quality of light (lumens and colour) should be increased;
- d.c. power supply for a small radio;
- 360° light spread (no shadows).

and four undesirable operational features in currently available lanterns, namely:

- blackening of the tube due to under-voltage lamp power supply (i.e., poor, or no, control of battery discharge voltage);
- switch failure due to poor component quality;
- no spares (tubes, lamps components, and batteries);
- short module leads (preventing roof mounting).

The average per capita income in Kenya approximates to the 'poverty line', and is estimated at about US$300 per annum. Unfortunately, the figure for the majority of Kenyans living in rural areas is likely to be significantly less, and the average per capita income available for expenditure on non-food items may be as low as US$50 – 100.

Table 1
Summary of critical product features in existing solar lanterns in order of importance to the end-user [2]

Ranking	Product feature
1	Reduced lighting cost
2	Light quality
3	Lantern portability
4	Appearance
5	Ease of use
6	Safety
7	Clean, environmentally friendly
8	Allows radio use

In remote areas, villages may have one lead – acid battery-powered television set, and solar panels are often used for recharging. This market sector is increasing rapidly and a significant proportion (~25%) of all lead – acid batteries sold in Kenya are for these solar-domestic applications (a typical system is comprised of a 12-V, 50 A h battery and a 20-Wp amorphous silicon module). A survey on solar electric systems in Kenya was financed under the Energy Sector Management Assistance Programme of the World Bank. It was estimated that between 2% and 5% of all rural and peri-urban households (i.e., 70,000 – 150,000 homes) were using a lead – acid battery (often an automotive 'car' battery) to satisfy their electricity needs. The rural districts surrounding Mt. Kenya (Meru, Embu, Nyeri, and Garissa), the Great Rift Valley (Nairobi and Nakuru) and Western Kenya (Kisii and Kisumu) are already important and popular regions for PV systems and are, therefore, prime locations for the new lantern. For many people, however, mains-power – or even lead – acid battery-power – is not affordable, and kerosene 'oil' lamps are commonly used for domestic lighting, as are zinc – carbon (Leclanché) and manganese dioxide – graphite primary cells for radios and radio/cassette players.

3. Product design specification

The product design brief was to produce a lighting unit that provides a maximum light quality to allow reading in any part of an average-sized rural room, offers a choice of light level (intensity), and is portable. The unit should be easy to operate by any member of the rural household, and should provide a minimum of 4 h of light in the evening time, on a daily basis. It should be able to withstand rough treatment, provide the user with information on the remaining duration of light, and have a power-connector for a 9-V radio. The lantern design should have a minimum operational life of 5 years, before replacement, and failure of the light unit must not create a dangerous situation to the user. In addition, maintenance of the light unit should be quick and easy, and the unit should be tamper-proof, in order to limit 'brand-name' damage through unauthorized modifications. The rural owner should have ready access to service and spare parts. Educational material on installation, usage and user-maintenance is to be provided with the light unit, at the point of sale.

Manufacturing assembly and testing of the lantern has to be simple. The unit must include a suitable charge controller in order to maximize battery life. The battery geometry is to be prismatic, and the battery design optimized for cyclic, solar system use. The battery must also

Fig. 1. CAD image of new ITC solar lantern (design subject to UK application for registration No. 203358) [3].

be spill-proof, require no 'topping-up' (water addition) during its operational life (i.e., maintenance-free), and its dimensions based on appropriate international standards and conventions. Lastly, the total system — comprising lantern, battery and PV module — must be affordable in that a valid cost benefit over kerosene, and other solar lighting products, is evident, whilst satisfying all of the above criteria.

A CAD image of the prototype 'micro-solar' lantern is shown in Fig. 1. ITC have applied for design registration protection of the lantern image design subject to UK Application for Registration No. 203358 [3].

4. Battery charging considerations

PV cells are solid-state devices (for example, monocrystalline or amorphous silicon thin-film cells) that convert photons of visible light directly into electricity. Such cells typically produce about 0.5 V per cell, and are connected in series and encased in a light-transmitting rigid structure to form modules (or solar panels). These modules may then be connected in series, parallel, or even series – parallel to give a PV array of the required d.c. voltage and current.

Below a certain load voltage, a PV module provides an almost constant current, which is proportional to the intensity of visible light falling on its surface. The global peak-sunshine hours (kW h m^{-2}/day), or insolation levels, clearly show a more than adequate energy resource, and this is particularly evident when examining the detailed monthly mean daily insolation levels for major cities and towns in East Africa, Fig. 2 [4].

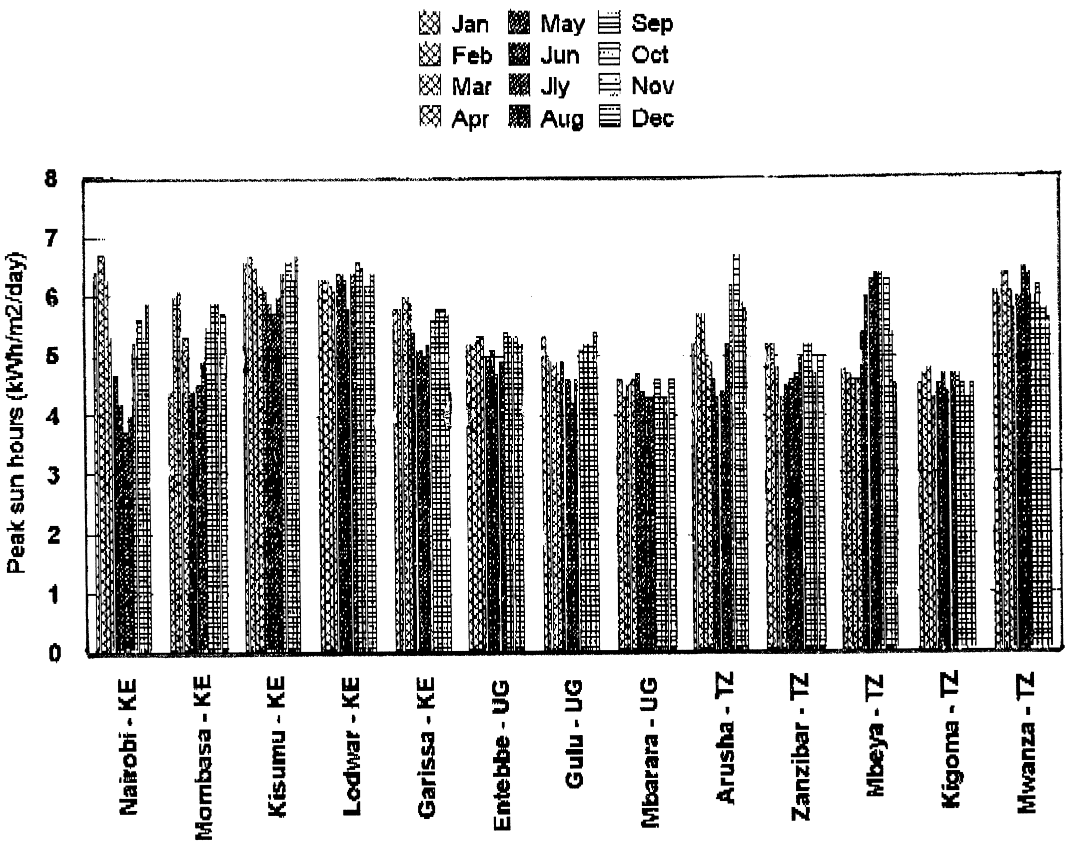

Fig. 2. Monthly mean daily insolation levels (in peak sun hours) for East Africa [4].

Protecting the battery from the effects of over-voltage and under-voltage is crucial if the operational life of the battery system selected for use in PV applications, such as the micro-lantern, is to be maximized. In most PV systems, however, the reality is generally the opposite. The system is generally under-sized, a charge controller is omitted on the grounds of cost-saving, and the often incorrectly-specified battery is subjected to an uncontrolled over-charge and/or overdischarge regime. This results in early battery failure, and customer dissatisfaction and scepticism in the value and efficacy of 'solar' energy. Spiers and Rasinkoski [5] have discussed in depth the critical aspects of predicting the service lifetime of lead – acid batteries in PV systems. The lead – acid battery, although generally very tolerant, can only withstand the effects of overvoltage (i.e., a charging voltage which is higher than the recommended 'float-charge' limit) for short periods of time. During overvoltage charge conditions, the battery may experience accelerated ageing (grid corrosion and loss of active material), generate (unwanted) heat and/or increased amounts of hydrogen gas. Excessive gassing leads to rapid depletion of the electrolyte and, particularly in the case of valve-regulated lead – acid (VRLA) batteries, drying-out. In some extreme cases, thermal runaway might eventuate. This operational requirement has been addressed in the design of the PV lantern control circuit, which has the following characteristics:

- proportional 'pulsed' charge regime,
- reverse-charge protection,
- state-of-charge (SoC) monitoring,
- high-voltage disconnect,
- low-voltage disconnect,
- recovery-voltage hysteresis detection,
- visible SoC indication,
- temperature compensation,
- programmable 'flash' memory,
- data-logging facilities.

5. Battery technology selection criteria and sensitivity analysis

In remote-area power-supply (RAPS) applications, particularly with PV home-lighting systems, the energy-storage component must have the following characteristics:

- good reliability under cyclic discharge conditions,
- low self-discharge,
- 'zero' maintenance requirement,
- high charging efficiency,
- wide operating temperature,
- robust design,
- low cost per watt-hour,
- high volumetric energy density,
- high gravimetric energy density,
- environmental 'safety',
- storage and use in any position (orientation),
- no need to be recharged immediately after discharge.

In addition to the ubiquitous lead – acid system, there are now emerging new battery systems that should also be considered when selecting a battery for use in the solar-lantern. Three commercially available alternative battery technologies, which fulfil most of the above performance criteria, and in particular, the critical requirements of being 'spill-proof' and 'maintenance-free', are reviewed.

6. Nickel – metal-hydride (Ni-MH) batteries

Ni-MH batteries have improved their performance especially in terms of volumetric energy density (typically 300 W h dm^{-3}, 5-h rate). Also, in excess of 500 charge – discharge cycles are now achievable from such batteries. The Ni-MH batteries, however, although possessing a substantially greater energy-storage capacity and power (per unit weight or volume) than lead – acid batteries, are prohibitively expensive (~ US$ 0.016 per W h, C_5/cycle at 80% depth-of-discharge (DoD)). A replacement battery is typically 10 – 12 times the price of an equivalent VRLA battery. This is due to the cost of the titanium – zirconium-based alloys, which are used in the manufacture of Ni-MH batteries, and the current technology for the production of Ni-MH battery electrodes, which is both complex and expensive.

In addition, Ni-MH batteries have relatively high rates of self-discharge, and it is difficult to terminate charging at full capacity (Ni-MH has a less pronounced voltage drop after reaching peak capacity). The latter increases the likelihood of overcharging, excessive heat generation, inadequate charged capacity, and shorter battery life. Charge control methods are, therefore, complex and termination is commonly based on the following techniques:

- cell temperature rise at the end of charge (dT/dt);
- peak cell voltage detection (V_{max});
- rate of decline in cell voltage after peaking ($-dV/dt$).

In general, whilst the Ni-MH battery is a good compromise between power, energy consumption and cost, the technology is more suited to less price-sensitive products, such as portable computers, cordless appliances and communication equipment.

7. Nickel – cadmium batteries

Nickel – cadmium batteries have the following attributes: proven durability under extreme operating conditions; high gravimetric and volumetric energy density;

good tolerance to overcharging, undercharging, reverse-charging, and deep-cycle discharge (> 500 cycles @ 80% DoD); low rates of self-discharge; superior lifetimes, particularly at elevated temperatures [6]. On the other hand, the batteries are more expensive than VRLA counterparts — the cost per cycle is typically four times that of a VRLA, viz., ~ US$0.004 per W h, C_5/cycle @ 80%DoD. The cost of original/replacement batteries is a significant factor for the end user, particularly since the solar lantern is aimed at a market sector which has, in general, only a small disposable income. A 10-cell, 12-V, 7 A h (C_5 rate) nickel–cadmium battery would retail at an estimated US$50–160, i.e., six to eight times the price of a comparable VRLA battery! The batteries are also susceptible to the 'memory' effect, i.e., when recharge is performed before full discharge, the electrodes passivate and decrease the ability of the cells to accept a complete charge.

Lastly, there are significant environmental issues associated with the disposal of 'spent' nickel–cadmium batteries, production wastes, and emissions collected from occupational hygiene systems and devices. Recent amendments to the Basel Convention [7] will restrict trade in waste materials destined for recycling, reprocessing and reuse. This gives rise to increased complications in the safe reprocessing of scrap and spent batteries.

For the above reasons, nickel–cadmium batteries must also be ruled out.

8. Lead–acid batteries

Uses for lead–acid batteries are numerous and diverse, and have resulted in various application-specific designs. Irrespective of the duty to be performed, however, the major battery selection criteria for a given application remain the same [8].

It has been reported [9,10] that gel designs of VRLA cells give encouraging performance when operating under simulated RAPS duty. This type of duty cycle is based on low discharge rates, deep discharge, and infrequent recharge. These early studies showed that, by contrast, absorptive glass mat (AGM) designs of VRLA cells/batteries gave considerably shorter life, mainly because of dry-out.

During the last decade, as a result of increased pressure to develop an advanced lead–acid battery for electric vehicles, much has been done to understand and advance the technology of VRLA batteries. The results of such research activities [11–15] have led to the following improvements:

- increased cycle-life at 50–80% DoD,
- less gassing,
- higher volumetric energy density,
- higher gravimetric energy density,
- improved power density,
- increased uniformity (quality),
- lower cost per W h,
- improved thermal management.

It is the authors' opinion, therefore, that VRLA batteries now offer the only realistic battery technology for the micro-solar lantern.

There are two distinctly different concepts for immobilizing the electrolyte within the cells of the VRLA battery, namely: AGM separators, and gel (thixotropic gelled) electrolyte. The 12-V, 7 A h (12N7) VRLA battery commonly imported and sold in Kenya uses AGM separator technology. The AGM design is, however, very sensitive to operating temperature such that service lives are reduced at elevated temperatures. Moreover, thermal runaway can occur under high-temperature conditions and result in the generation of large quantities of oxygen (which recombine exothermically), an increase in cell internal resistance, drying out of electrolyte, and swelling of the battery container. In extreme cases, meltdown of the lead components and battery explosion can also occur. In general, AGM-VRLA batteries cannot be designed to withstand the same temperature extremes as their gel counterparts, and ideally must have thermal management of both their charging current and surroundings if they are to provide acceptable service lives. They are, therefore, more appropriate for float-charge applications, such as uninterruptible power supply systems (UPS). Solar applications/use subject the battery to a rigorous, and often irregular, cyclic discharge–charge routine. Gel-VRLA technology has been shown [16–18] to be eminently more suitable for these applications.

Gel-VRLA batteries, specifically designed for use in PV applications, are now readily available from many the following manufacturers: Sonnenschein (Germany), 'Dryfit A200 Series'; SEC Industrial Battery (USA), 'Cellyte'; Battery Energy South Pacific (Australia), 'SunGel'. The performance characteristics of the Sonnenschein battery range have been reviewed by Tuphorn [19]. Whilst probably the most well-established gel-VRLA battery range available today, Dryfit batteries employ a proprietary (sophisticated) process to pre-sulfate the lead oxide prior to preparation of the paste and, therefore, requires costly process equipment. This is, perhaps, reflected in the somewhat higher final product cost. It has been shown, however, that these batteries have attributes that are well-suited to PV applications, in particular:

- very low self-discharge rate,
- no need to be recharged immediately after discharge,
- high cycle-life,
- can be used and stored in any position,
- may be subjected to a deep-discharge cyclic regime.

The Cellyte product range is limited; the smallest commercially available battery is a 12-V, 36 A h (100-h rate)

Table 2
Comparison of dimensions, weight, capacity, performance and cost of small AGM-, and gel-VRLA batteries commonly used in solar lanterns

VRLA battery type	AGM	AGM	Gel
Design application	(UPS)	(PV)	(PV)
Nominal voltage (V)	12	12	12
Nominal capacity (A h, C_{20} to 1.75 V/cell at 20°C)	7.2	7.2	5.7
Nominal capacity (A h, C_{100} to 1.80 V/cell at 20°C)	–	–	6.6
Weight (kg)	2.6	2.7[a]	2.2
Length (mm)	150	150	152
Width (mm)	65	65	66
Height (mm)	95	95	98
Volumetric energy density (W h (C_{20}) dm^{-3})	88.2	88.2	69.8
Gravimetric energy density (W h (C_{20}) kg^{-1})	33.6	32.0[a]	31.1
Self-discharge rate per month at 20°C (%)	3.2	3.0	1.7
Cyclic endurance to IEC 896 Pt. 2 (100% DoD)	~ 150	~ 200	~ 400
Cyclic endurance to IEC 896 Pt. 2 (80% DoD)	~ 200	~ 300	~ 500
Cyclic endurance to IEC 896 Pt. 2 (60% DoD)	~ 300	~ 450	~ 650
Cyclic endurance to IEC 896 Pt. 2 (40% DoD)	~ 700	~ 750	~ 1200
Replacement battery cost (US$)	~ 19	~ 20	~ 22
Energy cost (US$ per W h, C_5 cycle @ 80% DoD)	0.0017	0.0012	0.0010

[a] Estimated value.

unit. SEC also manufactures a comprehensive range of AGM-VRLA batteries ('Microlyte plus') but, as discussed earlier, these are not ideally suited for use in solar lanterns. It is significant to note that in moving from AGM to gel technology, whilst the capacity available from a given 12-V, prismatic battery reduces by ~21%, the battery energy cost per cycle remains fairly constant at about US$0.001 per W h. The performance characteristics and indicative costs of selected appropriate AGM-, and gel-VRLA batteries are compared in Table 2.

With the need for good product reliability and light-output, it may be necessary to design the lantern housing to accept an even larger capacity battery (e.g., a 14 A h, AGM-VRLA or an equivalent 10 A h, gel-VRLA unit). This may be required later for other more sophisticated, 'western' markets, which may also demand longer/brighter light output, and where initial cost is less of an issue. At this size, however, battery weight and its impact on lantern design and portability become key issues for market/user acceptability.

The Sungel battery produced by Battery Energy South Pacific, has been specifically designed and developed in Australia in conjunction with CSIRO and Telstra for use in PV energy-storage systems. The battery is made with state-of-the-art, VRLA Refined™, 'bismuth-bearing' lead oxide. This material has been developed specifically for use in VRLA batteries by Pasminco Metals (a major Australian lead producer and supplier to the battery industry) in collaboration with CSIRO [20,21]. This oxide is made from soft lead, which has a new and more stringent specification for purity [22]. The product —VRLA Refined™ lead — contains very low levels of impurity elements, which have been demonstrated to have a deleterious effect on VRLA battery performance. Bismuth is included in the product at a level that optimizes the enhancement in battery performance.

Sungel batteries are also assembled using pasted plates, which have been subjected to a carefully controlled paste-mixing, and 'hydrosetting' process. The latter favours the formation of tetrabasic lead sulfate ($4PbO \cdot PbSO_4 = 4BS$) in the cured plate. In order to generate the required proportion of basic lead sulfates (tribasic, $3PbO \cdot PbSO_4 \cdot H_2O = 3BS$ and 4BS) during paste mixing, special emphasis needs to be placed on selecting a paste mixer with the correct mixing/blending/shearing action, and on adequate process management systems for monitoring and controlling the mixing sequence, paste temperature, acid-to-oxide ratio (a predefined variable, which is often overlooked in determining an optimized paste for positive-plate manufacture), moisture content (paste density), and plasticity [23].

The effects of impurities in the positive and negative plates on the performance of AGM-VRLA batteries has

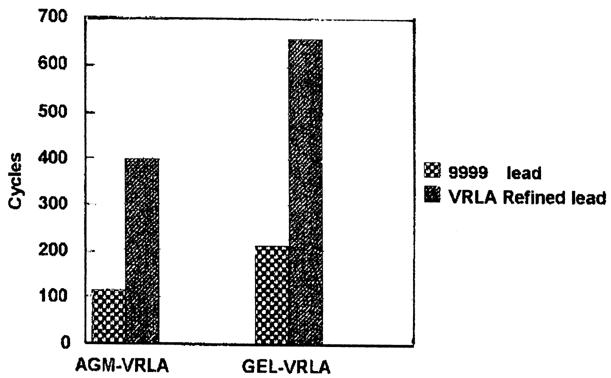

Fig. 3. Effects of 0.05 wt.% bismuth-bearing oxide (from VRLA Refined lead) on cycle-life performance of AGM- and gel-VRLA batteries under IEC test conditions [24].

been assessed in terms of self-discharge, water loss, grid corrosion, and charge efficiency [20,21]. Significantly, bismuth-bearing oxide has been shown to produce a low rate of hydrogen and oxygen evolution, and as a consequence, VRLA batteries made with 0.05 wt.% bismuth-bearing oxide exhibit a much lower (~50% less) rate of self-discharge. It has also been demonstrated that the capacity and cycle-life (under IEC test conditions) of both AGM- and gel-VRLA batteries is improved significantly by the use of bismuth-bearing oxide, see Ref. [21] and Fig. 3 Ref. [24]. Finally, it has been demonstrated [25] that AGM-VRLA batteries using bismuth-bearing oxide do not suffer from selective discharge of the negative or positive plates during float charging at constant voltage.

Small-sized, AGM-VRLA batteries, for example the NP™ series developed by Yuasa [26], have recently been optimized for cyclic applications. The new 'cyclic' NPC™ range offers improved endurance through the use of 4BS in the cured positive active-material and additional grid weight (reflected in a slightly reduced gravimetric energy density). If the capacity and cycle-life of the NPC range of AGM-VRLA batteries could be further enhanced by the use of bismuth-bearing oxide, with little or no increase in the cost of the battery to the end user, then this would represent a significant improvement in battery technology for the solar lantern, as well as for other PV applications.

9. Conclusions

In the authors' opinion, VRLA batteries based on the following product technologies represent the most suitable solution to the challenge of providing a state-of-the-art battery for the solar lantern project:

- gel electrolyte,
- bismuth-bearing lead oxide,
- tetrabasic lead sulfate in the cured plate.

Unfortunately, there is no currently available commercial battery that incorporates all of these features, and in a prismatic form relevant to the dimensional constraints of the proposed lantern.

In view of the relatively similar energy costs per cycle, it has been decided, therefore, that initial trials of lantern durability and light-output assessment shall be conducted with the A-200 series 12-V, 5.7 A h, gel-VRLA unit manufactured by Sonnenschein, and with the NPC series 12-V 7.0 A h, AGM-VRLA battery from Yuasa. It is hoped, however, that the anticipated success of this new, advanced solar lantern will prompt the design and development of a much needed, small, VRLA battery, which has been fully optimized for this demanding PV application.

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