www.czasopisma.pan.pl www.journals.pan.pl

ARCHIVES OF ELECTRICAL ENGINEERING VOL. 67(3), pp. 655–665 (2018)

DOI 10.24425/123670

Parameters estimation and life cycle economic analysis of a PV powered tri-cycle in India

SOUMYA DAS[1], PRADIP KUMAR SADHU[2], ANUP MAJHI[1], UDAYAN GHATAK[1], TUHIN BANDYOPADHYA[1]

[1] *University Institute of Technology, Burdwan University*

[2] *Indian Institute of Technology (Indian School of Mines), Dhanbad*
e-mail: soumya.sd1984@gmail.com

(Received: 12.04.2018, revised: 21.06.2018)

Abstract: This paper is devoted towards life cycle economic analysis (LCEA) of a solar photovoltaic (PV) powered tri-cycle. The paper is meant to propose a more systematic approach in determining the optimum use of scarce resources in order to determine the most cost-effective option of the solar tri-cycle. This analysis is based on the life cycle cost of this solar vehicle, involving its comparison with the customary fuel-based tri-cycle which exhibits the relatively less expenditure of the solar alternative. The economic analysis takes into account the fact that over 20 years, the overall price of solar component, replacement and electricity charges, is much lower as compared to that of a fuel-based tri-cycle in India taking into consideration the fuel cost, maintenance and annual inflation over the same period.

Key words: PV, tri-cycle, LCEA, fuel-based

1. Introduction

The economic prospects, its future and social advancement of a nation encompasses around the efficiency of its energy sector. Due to the unavailability of reliable supply of crude oil and other conventional fossil fuels the nation has failed to adequately make up for the current power scarcity, resulting in the poor living standards of the general mass and also acting as an impediment towards rural electrification of which these seem to be a better option purely on the basis of initial expenditure. Besides, in the long run, the total cost of energy generation for fuel run generators might not prove to be better than PV Panels in the same respect. The life cycle approach has earned a considerable attention of researchers due to its long-term cost differential [1–7, 10–11].

Concerns over pollution have led to increased popularity of unconventional energy sources these days aided by government support and private investment. Amongst them solar PV technology has stolen the lime light in nations like India due to the abundant availability of solar energy throughout the year. It is hailed as the potential solution to concerns over rising electricity cost and climate change.

Besides, the ever-increasing fuel price, the cost related to environmental pollution and the devastating impact on health due to the chemically hazardous emissions are the by-products of the conventional cars. These adverse effects being entirely absent in solar tri-cycles, bring them within the reach of the consumers. The industries manufacturing the solar tri-cycles can be financially supported by the savings from the government investments on the fuel-based tri-cycles. This will result in the reduction in price of the solar tri-cycles, thus, encouraging and influencing the general mass to purchase and avail them [8].

Moreover, in the case of bigger engines in a fuel-based car with higher power output, the fuel economy is very poor and the car is less efficient which results in an increased running cost. The solar cars are driven by an electric motor, which have high efficiency even if they are of higher rating and bigger size. Thus, a solar powered car with a bigger motor and higher rated power also has a good efficiency as compared to a fuel-based car. Also, electric motors ensure that the power delivery is instant and linear. Hence, a solar car has a huge surge of power from the beginning itself as compared to fuel- based cars, in which there is a lag in the power delivery at the beginning especially in turbocharged vehicles.

Analysis of the present worth of the various components of the fuel driven car, over a span of 20 years has been made. A comparative study involving the economics of driving such a car and a solar tri-cycle is also provided.

There are some generic principles for designing and modeling solar tri-cycles. The detailed design can be found in [8].

2. Proposed system design

Some comprehensive principles are involved for the modeling and designing of solar tri-cycles. The detailed design for the same can be found in [8].

2.1. Power of motor

For driving the solar tri-cycle, power is required which can be estimated utilizing the expression (1) as followed:

$$P = f \times v, \tag{1}$$

where v represents the velocity of the tri-cycle and f represents the required force for overcoming the friction acting between the road and the tires of the tri-cycle and the same can be evaluated as, [12]

$$F = M \times g \times C_{rr}\,. \tag{2}$$

Here, M denotes the mass of the solar tri-cycle, g is the acceleration due to gravity (which is 9.81 m/s^2) and C_{rr} denotes the coefficient of rolling resistance of the tire whose value varies widely for different types of car tires. The cause of this difference is due to the nature of load, type of road, nature of tires, kind of pressure applied etc. The tires used on the solar car are typical bicycle tires which have a rolling resistance of 0.0055 on asphalt/concrete roads.

The speed, at which the solar car will move can be assumed to be $v = 40$ km/h.

The mass of the solar car can be considered as:

$M = 600$ kg [car + battery + six occupants, including a driver] = (150 + 50 + 400) kg = 600 kg.

Therefore, about 360 W of maximum power (P) is needed to run the car but the motor chosen should possess at least 1.7 times the evaluated power rating owing to much larger friction due to uneven nature of roads in India. Hence a motor of power rating 650 W is suitable for the required condition.

2.2. Capacity of battery

The energy that is to be supplied by the battery determines the battery capacity which is in turn dependent on the total distance travelled. Let's consider the distance that the solar car travels be $S = 60$ km and the speed, at which it moves be $v = 40$ km/h. Then the solar tri-cycle travels a distance of:

$$S = v \times t, \tag{3}$$

or $t = 1.5$ h.

Thus, the total energy supplied by the motor is:

$$E_m = P \times t. \tag{4}$$

Since power necessity will vary based on the motor and condition of the road, the motor will certainly not be running at its rated power throughout the period of its operation. For the major part of time the motor will run at a minimum calculated power of 450 W taking into account the varying condition of the roads; poor residential lanes compared to better highways. The overall energy that the motor requires for the total distance to be covered can be judged by the following estimation. Let's consider the motor to run at a minimum calculated power of $P_{\min} = 360$ W for about 80% of time, for 10% of the time, it runs at a maximum power of $P_{\max} = 650$ W, and for the rest 10% of the time, it runs at the average value of these two $P_{av} = 505$ W. Thus from this assumed conservative estimate, the total energy required is given by [12]

$$E_m = \frac{1.1}{\eta_m}\left(P_{\max} \times 0.1t + P_{\min} \times 0.8t + P_{avg} \times 0.1t\right), \tag{5}$$

where η_m denotes the motor efficiency. Considering the loss of energy during each stoppage and start at the traffic signals and in bumper to bumper traffic, provisions have to be made for providing the loss of energy in such cases which is compensated by adding 10% energy to the total energy required. The battery shall provide this additional energy. The capacity of the battery will hence be determined by this factor.

Moreover, the car lights such as brake lights, head lights and turn signal lights are also to be powered by the battery itself. Therefore, the total energy requirement will constitute the energy required by the motor and the car lights. The determination of battery capacity involves the consideration of several factors. The actual ampere-hour (Ah) that the battery delivers stays always, compare to the ampere-hours (Ah) lost, which happens primarily due to the internal losses. In correspondence to the growth in the discharge current, the loss increases in a non-linear way according to Peukert's law. Peukert's law provides the relation between charge C_P lost in the battery and discharge rate I as [12]:

$$C_P = I^k \times t, \tag{6}$$

where t denotes the discharge time in hours and k denotes the Peukert coefficient which is usually 1.1 to 1.3. The actual discharge current (i.e. current drawn by a load) in amperes is I and t is the real time to discharge the battery. The capacity of one-ampere discharge rate is not generally provided for practical cells. Hence, to reformulate the law to a known capacity and discharge rate shall be beneficial to us:

$$t = H\left(\frac{C}{IH}\right)^k . \tag{7}$$

Here, H is the rated discharge time (in hours) and C is the rated capacity at that particular discharge rate, with I being the actual discharge current (in amperes). k denotes the Peukert constant and t is the actual time for the battery to discharge (in hours).

According to Peukert's law, the minimum battery capacity with changing motor requirement as needed for the complete trip is evaluated as, [12]

$$\begin{aligned} C &= 1.1\left[\left(\frac{P_{\max}}{\eta_m \times V_m} + \frac{nP_{HL}}{V_B}\right)\times 0.1t + \left(\frac{P_{\min}}{\eta_m \times V_B} + \frac{nP_{HL}}{V_B}\right)\times 0.8t \right. \\ &\qquad \left. + \left(\frac{P_{avg}}{\eta_m \times V_B} + \frac{nP_{HL}}{V_B}\right)\times 0.1t\right], \\ C &= 1.1\left[\left(\frac{P_{\max}}{\eta_m \times V_m} + \frac{nP_{HL}}{V_B}\right)\times 0.1 + \left(\frac{P_{\min}}{\eta_m \times V_B} + \frac{nP_{HL}}{V_B}\right)\times 0.8 \right. \\ &\qquad \left. + \left(\frac{P_{avg}}{\eta_m \times V_B} + \frac{nP_{HL}}{V_B}\right)\times 0.1\right]\times t, \\ C &= 20\ \text{Ah}, \end{aligned} \tag{8}$$

where the number of head lights is denoted by n, V_B being the battery voltage, P_{HL} being the rated power of car head light, $\frac{P_{HL}}{V_B}$ is the current require by the two headlights and the term $\frac{P}{\eta_m \times V_B}$ is the current of the motor while running at power P.

Two factors namely, temperature correction factor (K_{tcf}) and ageing factor (K_{af}) have to be included in accordance with ref. [12] and [14], so that sufficient energy supply to the tri-cycle during every winter of its useful life is ensured. To ensure a prolonged battery life, the maximum depth of discharge (DOD) must be limited within a certain value [16, 17]. After the consideration of all the above mentioned factors, the final capacity of the battery can be evaluated as follows:

$$\text{Battery capacity} = \frac{C \times K_{af} \times K_{tcf}}{\text{DOD}} = 35.71\ \text{Ah}. \tag{9}$$

So, a battery with 48 V, 40 Ah is suitable.

Table 1. Limiting values required to measure the capacity of the battery [12]

DC motor		
Maximum power, $P_{\max}$	650 W	
Minimum power, $P_{\min}$	360 W	
Average power, P_{av}	505 W	
Efficiency of the motor, η_m	90%	
Complete time of travel, t	1.5 hrs	
Car light		
Light	Power	Quantity of units
Car headlights	25 W	1
Brake lights	7.5 W	2
Signal lights	7.5 W	4
Parameters of the battery		
Battery voltage, V_B	48 V	
Peukart's number, k	1.1	
Temperature correction factor, K_{tcf}	1.00	
Ageing factor, K_{af}	1.25	
Maximum depth of discharge, DOD	70%	

2.3. Size of panel

The size of the panel is determined by the total energy to be provided by the battery alongside the battery losses and also the losses in the charge controller. If η_{ch} denotes the battery charging efficiency and the charge controller efficiency is denoted by η_{cc}, then the solar panels will require a total energy E_p and is given as [12]:

$$E_p = \left(\frac{C \times V_B}{\eta_{cc} \times \eta_{ch}}\right), \qquad E_p = 1185.18\ \text{J}. \tag{10}$$

Panel wattage:

$$W_p = \left(\frac{E_p}{h \times K_{df} \times K_{af}}\right). \tag{11}$$

Here, h denotes the solar isolation in hour, the derating factor which accounts for the decreased output caused due to accumulation of the dust layer on the surface of the panel is denoted by K_{df} and the ageing factor, which accounts for the decrease in panel efficiency over the years is denoted by K_{af} [15].

So, the wattage of the panel $W_P = 182.89$ W.

Table 2. Limiting values required to measure the panel size

PV panel	
Derating factor, K_{df}	0.9
Ageing factor, K_{af}	0.9
Panel efficiency, η_p	15%
Solar isolation, h	8 hrs
Charge controller	
Efficiency, η_{cc}	90%
Battery	
Efficiency, η_{ch}	90%

Four panels having 16–17 V output voltage and of 50 W should be connected in series for the fulfillment of the voltage requirement and wattage for charging the four series connected batteries. If solar panels of high efficiency ($\approx$ 15%) are to be used, an area of 1.33 m^2 is required to fit the desired panel.

On account of longer nights, poor sunlight and morning fog, the solar energy is certainly not sufficient. During the rainy season also, the solar energy is far from enough on account of the rain and clouds. This deficiency in energy can be provided by plug-in charging from the grid or some other alternate source. The electric drive system that comprises of the motor, battery and the panel and the ratings of the same have been summarized below in Table 3.

Table 3. Electric drive system of the solar car: design summary [12]

DC brushless motor drive	
Power rating	650 W
Voltage rating	48 V
Vented lead acid battery	
Capacity	40 Ah
Voltage	48 V
PV Panel	
Wattage	200 W
Output voltage	64–68 V

The rated power output of the motor is 650 W which is significant amount of power and also since it has 3 wheels; it has the advantage of lower drag and starting friction, which results in a higher speed whenever necessary. Also, it is fairly easy to direct and control a three wheeled car as compared to a four wheeled one.

Since in a solar car the wheels are driven by an electric motor, it gets instant surge of torque and power as compared to fuel based cars in which there is a lag until a certain R.P.M., which makes city driving a bit engaging in traffic conditions. The instant power delivery from the electric motor makes the solar car easier to drive and less engaging.

The main problem faced with a solar car is that the solar cells are unable to charge the battery on a rainy day or in the absence of sunlight. But that's not the case with this car since it also has the provision for charging the battery through electricity in the absence of sunlight. Thus, this car can also be used in the rainy season, when the sunlight is absent for a few days.

3. Economic analysis

This section comprises the overall economic utility and desirability of a PV powered tri-cycle over the usual fuel driven tri-cycle. A methodology termed life cycle cost (LCC) analysis is undertaken progressing on similar lines in order to estimate and evaluate the economic effect of present and future cost. Thus, the entire expenditure borne due to the vehicle right from its installation to its decommissioning is included in the life cycle cost analysis [15].

3.1. Life cycle cost analysis of solar tri-cycle

The LCC of the solar tri-cycle firstly involves the evaluation of the general trend of the cost of a solar panel, its useful life time, its installation cost, the requirement of repair or replacement and lastly the cost linked with the panel operation and the battery alongside their maintenances. The recorded statistics over the last few decades reveal with the increase in demand of the solar panels, a reduction in their cost has resulted. Thus, the availability of more user-friendly, efficient and economic panels in the future can be guaranteed [13]. The high initial cost of its installation is compensated by the long lifetime of the panel. About 20 to 25 years of successful operation without the need of any crucial replacement is estimated, which makes them cost-effective in the long run.

Electric lead-acid batteries also do not need regular replacements on account of good life expectancy of 5 years [9]. The cost of operating and maintaining the panels and the battery are also comparatively less on account of self-dependent nature.

Therefore, the motors, charge controllers and batteries are required to be replaced several times before the replacement of the solar panels. Thus, all the expenses incurred by a solar panel in one life time, which consist of the panel cost, installation cost and the cost of replacing the battery (over a period of 20 years/5 years) for 4 times, the expenses for replacing the DC motor twice and the charge controller, constitute the overall cost of the solar commuter.

3.2. Present worth

The present worth (PW) of all the essential parts of the system are required to be computed and then added for determining the LCC of the solar tri-cycle. The current worth of money that is needed to be invested at the present time in order to purchase the product 'n' years later gives the present worth of the product, assuming theinflation rate and interest or discount rate being $100i\%$ and $100d\%$ respectively, which is given by [12]

$$PW = \left(\frac{1+i}{1+d}\right)^n \times C_0, \tag{12}$$

where C_0 is the initial cost of the product at the time of investment [8, 15]. The recurring expenses occurring every year which eventually add up to the overall cost should be accounted for and for doing so the cumulative PW is determined by taking the sum of the individual PW of every element of the product in series. The following expressions [15] are used to evaluate the expenses such as cost of fuel and maintenance cost.

$$PW = \frac{1 - x^n}{1 - x} \times C_0 , \tag{13}$$

$$x = \frac{1 - i}{1 + d} . \tag{14}$$

In India, the average rate of interest and inflation has been evaluated to be 5% and 7% (approximate), respectively. The cost per unit of the several components needed for the operation of the solar tri-cycle has been determined by conducting a local market survey. The life cycle cost analysis of running a solar car can be calculated by comparing all these costs and their quantities required, as depicted in Table 4.

Table 4. LCC analysis of a PV powered tri-cycle

Component required	**Number of units**	**Unit cost (INR)**	**Initial cost (INR)**	**Present worth (INR)**
Solar panel	4	76 per watt	15 200	15 200
Battery	4	7 000	28 000	28 000
Battery (5 yrs.)	4		28 000	25 480
Battery (10 yrs.)	4		28 000	23 186
Battery (15 yrs.)	4		28 000	21 095
Charge controller	1	3 700	3 700	3 700
Charge controller (10 yrs.)	1		3 700	3 064
DC motor	1	3 500	3 500	3 500
DC motor (10 yrs.)	1		3 500	2 898
Annual maintenance			2 000	33 632
Life cycle cost				159 755

The additional cost of electricity to drive the solar car by the power supplied through main line electric supply are also taken into consideration on account of insufficient solar energy. The tariff of electricity supplied by West Bengal State Electricity Distribution Company Limited (WBSEDCL) is INR 6.5 per kWh of usage for residential use for home and business consumers with an average consumption over 400 units. The overall cost of operating the solar car at different rates (%) of the total energy required, with supplementary electricity from the main lines is depicted in Figure 1. In every case, the evaluation of cost takes place for a span of 20 years considering 300 days of commuting. The operational cost of the solar tri-cycle is also evaluated for the same. For suitable comparison, in a span of 20 years, the cost of driving a conventional fuel driven tri-cycle is also required to be calculated.

The average mileage of a fuel-based tri-cycle (auto rickshaw) in the city is about 20 to 25 km per litre. However, the distance travelled per litre is decreased to a maximum of 15 km on account of traffic congestions. For a period of 20 years and an average distance of 70 km on every working day of the month with the present fuel price of INR 64.2635 per litre, the operational cost of the car is evaluated below.

When the LCC of running a solar tri-cycle as determined in Table 4 and that of a fuel driven tri-cycle, determined in Table 5 are compared, the fact that solar tri-cycle is significantly cheaper to operate than gasoline cars becomes clear. Along with the costs evaluated above the costs in terms of environmental and health hazards is also required to be considered. It can be ascertained that both quantitatively and qualitatively the long term cost of running a fuel driven tri-cycle is much higher as compared to the cost of utilizing and maintaining a solar fuel-based tri-cycle.

Initially it was evaluated that a 650 W motor is capable of running the solar car while 48 V batteries having a capacity 40 Ah and a 200 W solar panel are sufficient for providing the necessary power to run the motor and thus drive the wheels of the car. Its reemphasized through calculations revealing the fact that in spite of the maximum operating cost of a solar car along with electricity usage is approximately INR 88 thousand which is very less as compared to the least running cost of a fuel powered car (about INR 13 lacs 3 thousand) by the combustion of 1 050 litres of fuel, annually.

Table 5. LCC analysis of a PV powered tri-cycle

Component	**First year (INR)**		**Present worth (for 20 years)**	
	without congested traffic	with congested traffic	without congested traffic	with congested traffic
Fuel	67 476	83 136	1 134 660	1 398 000
Yearly maintenance	10 000		168 160	
Engine oil, tax, fitness test, servicing, filter replacement	8 000		134 530	
Total operational cost			1 437 350	1 700 690

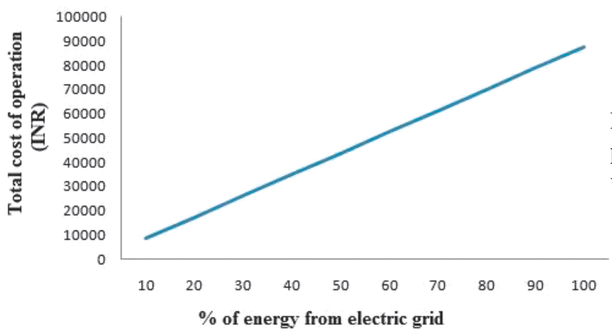

Fig. 1. Life cycle cost of operation of a PV powered tri-cycle with plug-in electricity for various percentage of total required energy from electricity grid

4. Conclusions

The compelling case made by alternative sources of energy more specifically solar energy is substantially emphasized in the above analysis which has been engineered to suit a particular transportation need of a suburban town. The solar photovoltaic (PV) powered tri-cycle has undergone a life cycle economic analysis (LCEA). The calculations in this paper reveal the fact that even considering the highest operating cost of a solar car along with electricity usage is fairly less than that of a fuel-based car. Thus, the solar car is a more practical, economical and environment-friendly option as compared to a fuel powered car. A solar powered car also has less complications as compared to a fuel-based car since its system primarily include the solar cells, a battery and an electric motor to drive the wheels. On the contrary, the design of an engine of a fuel-based car is far complicated mechanically and requires several different components such as radiator, spark plugs, cylinder heads, camshafts etc. Thus, a solar powered car is easy to assemble and also easy to repair since there are very few essential components.

Fuel based cars emit toxic exhaust fumes and gases to the environment, causing a devastating effect on Mother Nature and her beings. Also, the prices of fuels are rising day by day and thus the running cost of fuel-based cars is also increasing. This is a cause of common man's suffering and it can be overcome by the use of a solar car. Progressing on the planks of the solar panels multifaceted benefits and some tailwinds in the form of the reduction in the cost of a solar panel and externalities cost and assistance from the government will cause the solar cars to evolve as the most economically sound and user-friendly car in the days to come.

References

[1] Roy A., Kabir M.A., *Relative life cycle economic analysis of stand-alone solar PV and fossil fuel powered systems in Bangladesh with regard to load demand and market controlling factors*, Renewable and Sustainable Energy Reviews, vol. 16, pp. 4629–4637 (2012).

[2] Agustin J.L.B., Lopez R.D., *Economical and environmental analysis of grid connected photovoltaic systems in Spain*, Renewable Energy, vol. 31, pp. 1107–28 (2005).

[3] Byrne J., Zhou A., Shen B., Hughes K., *Evaluating the potential of small-scale renewable energy options to meet rural livelihoods needs: a GIS- and lifecycle cost-based assessment of Western China's options*, Energy Policy, vol. 35, pp. 4391–401 (2007).

[4] Oparaku U., *Rural area power supply in Nigeria: a cost comparison of the photovoltaic, diesel/gasoline generator and grid utility options*, Renewable Energy, vol. 28, pp. 2089–98 (2003).

[5] Qoaider L., Steinbrecht D., *Photovoltaic systems: a cost competitive option to supply energy to off-grid agricultural communities in arid regions*, Applied Energy, vol. 87, pp. 427–35 (2009).

[6] Kolhe M., Kolhe S., Joshi J.C., *Economic viability of stand-alone solar photovoltaic system in comparison with diesel-powered system for India*, Energy Economics, vol. 24, pp. 10–16 (2002).

[7] Das S., Sadhu P.K., Chakraborty S., Saha M., Sadhu M., *Life cycles, economic analysis of stand-alone solar pv system in India – a relative study*, World Journal of Engineering, vol. 12, iss. 1, pp. 37–44 (2015).

[8] Das S., Sadhu P.K., Chakraborty S., Dhara S., Sen S., *Design and Implementation of A PV Powered Tri-Cycle*, Current World Environment, vol. 11, pp. 1–6 (2016).

[9] Celik A.N., Muneer T., Clarke P., *Optimal Sizing and Life Cycle Assessment of Residential Photovoltaic Energy Systems With Battery Storage*, Progress in Photovoltaics: Research and Applications, vol. 16, pp. 69–85 (2007).

[10] Iskander C., Scerri E., *Performance and cost evaluation of a stand-alone photovoltaic system in Matlab*, in: Proceedings of the WREC 1996, pp. 437–440 (1996).

[11] Hiranvarodom S., *PV systems installed at a Thai university for PV development: real lessons learnt*, in: Proceedings of the WCPEC 2006, pp. 2407–2410 (2006).

[12] Ahmed S., Zenan A.H., Rahman M., *A Two-Seater Light-Weight Solar Powered Clean Car: Preliminary Design and Economic Analysis*, 3rd International Conference on the Developments in Renewable Energy Technology (ICDRET) (2014).

[13] Wahi R.R.-H., Ahsan N., *Feasibility Study of Solar Home System in Rural Areas of Bangladesh: Prospect, Progress and Challenges*, Proceedings of the Global Engineering, Science and Technology Conference, Dhaka, Bangladesh (2012).

[14] Wakefield H.E., *History of the Electric Automobile-Hybrid Electric Vehicles*, Society of Automotive Engineers, vol. 187 (1998).

[15] Messenger R.A., Ventre J., *Photovoltaic Systems Engineering*, Second Edition, CRC Press LLC, pp. 145–155 (2004).

[16] IEEE Std. 485 TM-1997, IEEE Recommended Practice for Sizing Lead – Acid Batteries for Stationary Applications (1997).

[17] IEEE Std. 450 TM -2002, IEEE Recommended Practice for Maintenance, Testing and Replacement of Vented Lead-Acid Batteries for Stationary Applications (2002).