Numerical investigation for high lifetime solar-powered airport signal unit development

A B Tarasenko¹* and A A Fedotov¹,²

¹ Joint institute for High Temperatures, Renewable Energy Laboratory, Izhorskaya Street No. 13/19, Moscow, Russia
² National Research University Moscow Power Engineering Institute, Chemistry and Electrochemical Energy department, Krasnokazarmennaya Street No.1, Moscow, Russia

Email: a.b.tarasenko@gmail.com

Abstract. Autonomous solar-powered small light and signal units can help solve many navigation and transportation problems for sufficient solar energy potential regions. Even in case of centralized grid presence the additional consumers’ integration can be an issue due to construction works and power availability. Electrochemical accumulator is a traditional solution for such devices, but its application usually faces lifetime and stable operation at low temperatures problems. Electrochemical double-layer supercapacitor (EDLC) possess high cyclic resource and stable operation down to minus 40-45°C. Low specific energy capacity, high specific energy costs and high self-discharge rates are main drawbacks for this technology. The paper is devoted to airport signal unit operation numerical simulation in case of lead-acid accumulator and EDLC application. Using developed software based on energy balance calculation and satellite solar energy data, optimal configurations of signal units were derived for Rostov and Saratov climate conditions. Technical and economical estimations for both configurations were made from the 100% operation availability and minimum service during 20 years – typical lifetime for monocrystalline photovoltaic module. Maximum power point tracking (MPPT) charge controller features typical for such application are also considered. Target parameters for EDLC commercially attractive application were evaluated.

1. Introduction.

It is known, that operation of electrochemical batteries at low temperatures usually causes problems which are more serious than temperature is lower. Russian Federation has a large part of its territory covered with cold climate zone. But in many regions with low temperature transport and infrastructure objects must be operated. Modern transport infrastructure also include airports, especially for regions with high area and signal light units are used to provide stable and safe operation of such objects. Autonomous solar-powered small light and signal units can help solve many navigation and transportation problems for sufficient solar energy potential regions. Even in case of centralized grid presence the additional consumers’ integration can be an issue due to construction works and power availability. Such autonomous solar-powered unit include photovoltaic (PV) panel, charge controller and energy storage device to provide night operation of light source usually based on light-emitting diodes (LED) technology. Energy storage device is a most problem component of the whole unit – usually lead-acid electrochemical battery is used, causing problems with lifetime, low depth of
discharge and low temperature operation. Average lifetime for modern PV panels is about 20 years, for charge controllers – about 10 years, due to electrolytic capacitors drying out and for lead-acid battery – about 4-5 years. Battery change, considering battery share in capital costs of the light-signal unit as 60-70%, significantly increases payback period for any solar-powered devices. Cold climate operation usually increases PV panel energy output, but drastically worsens battery operation. At high temperatures lead-acid batteries are prone to fastened degradation. Attempts to decrease temperature influence by situating battery underground make the whole system more expensive and complicated. So the task of this research is attempt to find alternate to lead-acid battery storage devices which will be able to provide comparable lifetime with PV panel and charge controllers. In [1] similar motivation led to introduction of vanadium flow battery and supercapacitors into grid-tie PV park for power fluctuations mitigating. Main purpose of this research is to estimate supercapacitors application possibility as energy storage devices for autonomous light-signal solar powered units. Though their specific energy cost, their high lifetime (about 1 mln cycles) and stable operation at low temperatures give them a chance for successful competition with lead-acid battery.

2. Energy storage cold climate operation
Russia is one of the coldest countries in the world, permafrost occupies about 65% of the entire territory of Russia. The largest areas of permafrost are Eastern Siberia and Transbaikalia [2]. This circumstance causes certain problems when using equipment operating electrochemical energy storage devices. The climate map of the Russian Federation is shown in Figure 1. During electrochemical energy storage device operation an incomplete battery discharge at low temperature is a typical situation. Often the ambient temperature is below 0 °C and it is necessary to keep the equipment running smoothly. Without an external source of heat or electricity in these conditions it is impossible [3].

![Figure 1. Duration of periods with temperatures less than 10 degrees Celsius, hours per year](image-url)

In [4], energy output measurements were made for various batteries and supercapacitors at temperatures below zero. Climatic tests have shown that only organic electrolyte-based supercapacitors (curves 1 and 2) retain almost nominal energy capacity, efficiency and power output in a wide temperature range below zero. For other types of tested electrochemical batteries, the residual energy capacity decreases sharply in the zone of low temperatures, as well as with an increase in the discharge current.
3. Supercapacitor and lead-acid battery unit operation calculation

The purpose of the calculation is to determine the optimal composition of the autonomous power supply system for taxiway lights for airports and compare lead-acid batteries and supercapacitor modules as storage devices for such systems. The most suitable optimization object is a taxiway light with a peak power of 1 W [5]. Due to the low power required a relatively low power consumption, which can be provided by supercapacitors. Since the technical and economic indicators of photovoltaic power objects are highly dependent on the point of their location, pilot facilities are needed for the calculations. The airports of «Tsentralny» (Saratov) and «Yuzhny» (Rostov-on-Don) were chosen as pilot sites for implementation. Both airports are located in regions with relatively high level of insolation.

It is assumed that each taxiway light will be equipped with its own power supply system, including the highly efficient photovoltaic module Hevel HJT 300 (peak power 300 W, efficiency 18%, heterojunction with intrinsic thin layer technology). Also each taxiway light will be equipped with supercapacitor or lead-acid battery with a charge controller and a direct current converter for the supercapacitor battery to the voltage level of 24 V. The charge controller provides the charge of the super-capacitor battery from the photovoltaic module with maximum power point tracking (MPPT), limiting the amperage and voltage of the charge-discharge process of supercapacitor or lead-acid batteries. Also it provides communication with its own control and management system, the inclusion and disconnection of the load. The important issue is that different controllers are needed for lead acid battery (10.5-15 V operational voltage range) and supercapacitor (8-16 V operational voltage range) for better energy utilization. So estimation involves more expensive controller for supercapacitors.

During the calculations, two possible locations of the photovoltaic module were considered. Horizontal, which allows it to be mounted in the runway next to taxiway light. Another option is to place a little bit away from runway, and at an angle of inclination to the horizon, equal to the angle of latitude + 15 degrees (minimum snow-covered of the module in winter).

Special software to estimate solar-powered units operation has been developed in Joint Institute for High Temperatures. Input climate data - daily satellite observations on temperatures and solar radiation sums on a horizontal surface from the NASA Power database [6] from 1987 to 2016, unit location coordinates and UTC time zone. The recalculation of the amounts of solar radiation at given tilt angle of the PV panels was carried out using the approach described in [7]. Input data on key components include PV panel area and peak power, energy storage device efficiency, energy capacity, operation voltage, charge controller peak power and efficiency-on-power dependence. Costs of all components are also used to estimate capital costs for solar-powered light-signal unit. Consumer power demand, its time dependence and demanded power availability are also chosen by user before calculation. Having all this initial data, software is calculating hour temperature, insolation and energy balance of solar powered unit choosing enough components to reach given power availability during the whole calculation period. Energy balance of the whole power unit is calculated for each hour from January, 1987 to December, 2016. Power availability during the whole night throughout this period is given as necessary border condition for calculation. The same availability can be reached at different combinations of PV panels and batteries, so software generates up to 10 such combinations (increasing number of PV panels, usually from 1 to 10 pcs) with their capital costs, giving consumer possibility to chose one with suitable cost and battery average depth of discharge (influencing battery lifetime).

Capital costs for each combination are estimated as sum of storage system, PV panels and charge controller costs. Results for such optimization, considering Rostov-on-Don site, are given at figure 2. Because software was initially developed for batteries, energy capacity of supercapacitor module (16 V, 500 F) was estimated as 1,2 Ah, considering 12 V as average operation voltage and 8-16 V as full operation voltage range. Self-discharge rate of 35% per month for supercapacitor and 3% per month for lead-acid battery was also taken into account.
Figure 2. Optimization results for Rostov-on-Don site, taking into account 50 Ah, 12 V lead-acid battery and 500 F, 16 V supercapacitor module. Horizontal PV panel orientation.

4. Results and discussion
Calculations were carried out for single solar-powered LED unit with a load power of 1 W, operating the whole day. Calculation results are given in Table 1. Components parameters for calculation were following – 300 W peak power for PV panel, 16 V DC voltage and 500 F capacity for supercapacitor battery. 24 V DC is chosen as a DC bus operation voltage to feed LED unit.

Table 1. Calculation results for solar-powered signal light unit using supercapacitors as energy storage device.

| Airport  | Panel tilt angle, ° | PV panel, pcs | Supercapacitor modules, pcs | MPPT controllers, pcs | Maximum storage device depth of discharge, % | Components cost, RUR |
|----------|---------------------|--------------|-----------------------------|-----------------------|---------------------------------------------|---------------------|
| «Tsentralny» | 0                  | 1            | 2                           | 1                     | 69                                          | 70370               |
| «Tsentralny» | 71                 | 1            | 2                           | 1                     | 75                                          | 70370               |
Close cost value for both sites can be explained by given parameters of PV panel and supercapacitor – software is able operate only with integer amount of components, and the set of PV panel and supercapacitor battery is sufficient for load cover at both sites. Results for the same sites with lead-acid batteries are given in Table 2.

Table 2. Calculation results for solar-powered signal light unit using lead-acid batteries (50 Ah, 12 V) as energy storage device.

| Airport   | Panel tilt angle, ° | PV panel, pcs | Lead-acid batteries, pcs | MPPT controllers, pcs | Maximum storage device depth of discharge, % | Components cost, RUR |
|-----------|---------------------|---------------|--------------------------|-----------------------|---------------------------------------------|----------------------|
| «Tsentralny» | 0                   | 1             | 2                        | 1                     | 30                                          | 46845                |
| «Tsentralny» | 71                  | 1             | 2                        | 1                     | 30                                          | 46845                |
| «Yuzhny»   | 0                   | 1             | 2                        | 1                     | 49                                          | 39385                |
| «Yuzhny»   | 62                  | 1             | 2                        | 1                     | 49                                          | 39385                |

Calculation showed stable system operation with 50 Ah batteries and much less capital costs than in case of supercapacitors, but energy capacity loss at low temperatures must be taken into account. So real costs for stable-operated system can be estimated at about 50 thousands of rubles. Battery change is supposed to occur once in 5 years, so close payback period for supercapacitors can be achieved only in case of 20 years supercapacitor lifetime and supercapacitor costs needs decreasing, though supercapacitor also allow deeper discharge. Further increase of solar panel amount is undesirable due to unit surface area and capital costs increase. Charge MPPT controller algorithm for such application must take into account high self-discharge rate of supercapacitor batteries, so self-consumption in periods, when load is fed from supercapacitor battery must be minimized. Due to stable supercapacitor operation at wide temperature range temperature compensation for voltage can be neglected. For reasons of higher lifetime electrolytic capacitors application in such controllers must be limited.

5. Conclusions
Numerical simulation of autonomous solar-powered light signal unit for airports was performed for two locations in Russia using original software for energy balance of solar-based power units and satellite-based initial climate data to compare performance and capital costs for autonomous solar-powered units with supercapacitors or lead-acid batteries as an electric energy storage devices. Calculation included optimal device configuration for both lead-acid and supercapacitor storage system. 300 W peak power PV panel and 50 Ah 24 V lead acid battery (or 250 F 32 V supercapacitor battery) are enough for stable operation of 1 W LED light signal device in Saratov or Rostov-on-Don climate conditions. It was shown that lead-acid battery has cost advantage. But low lifetime and capacity loss at low temperatures give chance for supercapacitors application in case when their
lifetime will achieve 20 years, as for monocrystalline PV panel. Such approach can realize more expensive system than in case of lead-acid batteries but it can be operated for 20 years without maintenance and battery change. Possibility to create such unit is shown and cost estimation is made due to high supercapacitors lifetime and stable operation at low temperatures. Special charge controller for such system is needed – with extended operation voltage range and low self-consumption.

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