DOI: 10.71762/2gac-z583

Research Paper

The Effect of Manufacturing Method and Material Type on the Solar Battery Charging Rate

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Received: July 29, 2025; Revised: September 23, 2025; Accepted: October 4, 2025

Abstract
Photovoltaic (PV) batteries exhibit distinct mechanical properties that render them well-suited for integration into solar energy systems. These properties include the ability to withstand mechanical stresses, such as bending or pressure, during the handling, installation, and operational phases of use. High durability is essential to ensure consistent performance across diverse environmental conditions over their extended service life. This study presents empirical data derived from laboratory testing of solar cells, with a focus on comparing the battery charge percentage displayed by a 12/24V charge controller against theoretically estimated values. The calculations are based on the voltage difference (ΔV) between the open-circuit voltage (Voc) and the minimum standard battery voltage. The analyzed results were normalized into percentages, resulting in the development of an equation that demonstrates strong alignment with experimental observations. A comparative assessment of various battery technologies is presented, along with an investigation into the mechanical properties of solar cells. The findings indicate that advanced materials, including perovskite and monocrystalline silicon, when combined with optimized manufacturing techniques such as roll-to-roll processing and laser scribing, significantly improve charging efficiency.

Keywords
Solar Battery, Charge Estimation, Mechanical Characteristics, Depth of Discharge (DoD), State of Charge (SoC)

1. Introduction

Solar energy conversion is a fundamental component of sustainable energy solutions, utilizing the abundant photon flux from sunlight. However, its intermittent nature, caused by weather fluctuations, day-night cycles, and seasonal variations, requires efficient energy storage to ensure grid stability [1]. Battery management systems (BMS) play a crucial role in enhancing battery longevity, system reliability, and cost efficiency [2]. A reduction in battery prices can increase the economic viability of battery installations [3]. Additionally, lower net billing rates lead to greater demand for battery storage [4]. Progress in battery technology, from Volta's first electrochemical cell (1800) to contemporary lithium-ion systems, has been essential for integrating renewable energy [5]. Data collection relies on measurements from a charge controller equipped with a display.

Depth of discharge (DoD), expressed as the ratio of discharged capacity to total capacity, significantly affects battery lifespan. A lower DoD is associated with prolonged battery life and better warranty conditions. Deep discharges (80–100% of the nominal capacity) and excessive charging voltages (more than 20% above the nominal value) accelerate battery degradation. However, solar applications frequently operate outside ideal charging conditions (10% of rated Ah) due to limited peak sun hours (PSH). The nonlinear characteristics of battery charge/discharge curves further complicate the accurate estimation of state of charge (SoC).

Lead-acid (LA) batteries remain a common choice for energy storage due to their affordability and low maintenance needs [6]. Nevertheless, they suffer from notable drawbacks, such as poor resilience to deep discharges and subpar performance in cyclic use. Additionally, LA batteries exhibit insufficient voltage regulation during discharge, with significant voltage drops under high discharge rates. The charging process typically employs a hybrid method, combining constant-current and constant-voltage phases to enhance charge efficiency while preventing overcharging. This two-stage approach helps address the inherent electrochemical constraints of lead-acid technology.

2. Solar Batteries Technology

Various types of batteries are used in solar energy storage systems, each with distinct characteristics and suitability for different applications. The battery is a crucial component in Solar Home Systems (SHS), storing the energy generated by photovoltaic (PV) panels. Despite its essential function, batteries account for the highest initial cost in SHS installations [7]. Proper battery sizing plays a significant role in determining operational lifespan. Oversizing the battery bank for a specific application reduces the average Depth of Discharge (DoD) per cycle [8]. This relationship follows an inverse correlation: lower cycling depths slow down degradation mechanisms, thereby prolonging battery life. Sizing optimization must strike a balance between upfront costs and long-term performance benefits, as excessive capacity may lead to diminishing returns while significantly raising the initial investment. The DoD can be calculated based on the battery discharge current over a discharge period, as shown in Equation 1 [8]:

$$DOD = \frac{\int_{t_i}^{t_f} I_{discharge}.dt}{C_i} \tag{1}$$

Where t_f is the time at the end of the discharge interval process, ti is the initial time, Idischarge is the discharge current, and Ci is the initial battery capacity [8]. Numerous models that predict the expected lifespan of a battery depend on the operating conditions and the charge and discharge cycles [9].

Standalone solar PV/battery (SSPVB) systems have emerged as a prevalent solution for electrification in remote areas. The battery energy storage (BES) component plays a pivotal role in these systems, ensuring a continuous power supply by mitigating the intermittent nature of solar generation.

Solar batteries commonly rely on two main chemical technologies: lithium-ion and lead-acid. Among lithium-ion variants, Lithium Iron Phosphate (LFP) and Nickel Manganese Cobalt (NMC) stand out for their superior energy density, extended longevity, and minimal maintenance needs. In contrast, lead-acid batteries, while more affordable and well-established, tend to have a shorter operational lifespan and require more frequent upkeep.

Further improvements in the performance and cost reduction of Li-ion and solid-state batteries can be achieved by minimizing variations in their physical and electrical properties. These properties can be optimized and standardized through the integration of battery electrical models and the adoption of innovative manufacturing techniques. For instance, UV-assisted photo-thermal processing, which leverages the quantum photo effect, can reduce metal surface roughness. Additionally, in-situ measurements combined with advanced process control (APC) can ensure uniformity across individual electrochemical cells [10]. Lithium-ion batteries are widely regarded as the leading solution for modern energy storage technologies due to their exceptional performance characteristics. They provide high energy density, low self-discharge rates, extended cycle life, high open-circuit voltage, and negligible memory effects. These advantages collectively position lithium-ion technology as a premier choice for addressing contemporary energy storage challenges [11]. Nickel-based batteries, on the other hand, offer notable environmental and safety benefits. Flow batteries, a relatively recent development, boast a long lifespan, high energy density, and the ability to function efficiently across a broad temperature range, albeit at a higher cost.

Detailed schematics of solar battery internals are not always readily available. However, the operational principles of conventional batteries can serve as a helpful reference for fundamental understanding. Figure 1 illustrates a cross-sectional view of a standard cylindrical Li-ion cell, annotated to highlight key components, including primary electrodes, coils, and charge movement. Comparisons of technology between various battery types are presented in Table 1. This table outlines the types of batteries, along with their advantages and disadvantages.

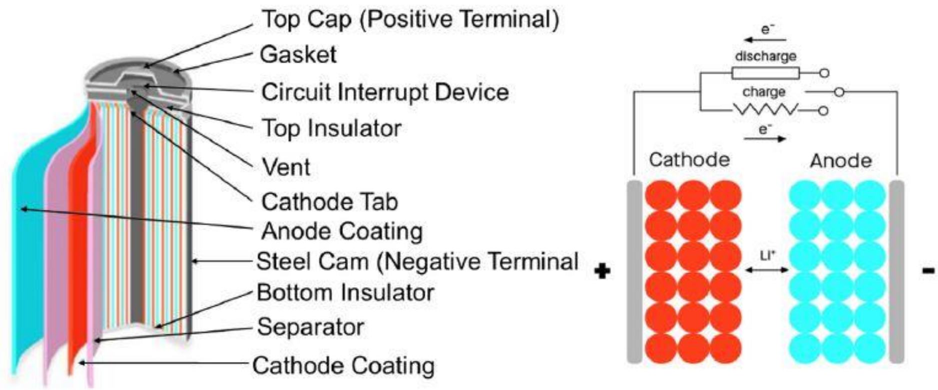


Figure 1. A cross-section of a typical cylindrical Li-ion unit cell depicting the essential working of a Li-ion cell [12]

The general characteristics of the most commonly available batteries are presented in Table 2, which categorizes electrochemical cells according to parameters like energy and power density, cycle life, cost, efficiency, and self-discharge rate.

Table 1. Technology comparisons between various battery types [13]

Battery Type	Advantages	Disadvantages
Flow battery	(i) Independent energy and power rating (ii) Long service life (10,000 cycles) (iii) No degradation for deep charge (iv) Negligible self-discharge	(i) Medium energy (40-70 Wh/kg)
Lithium-ion	(i) High energy density (80-190 Wh/kg) (ii) Very high efficiency 90-100% (iii) Low self-discharge (1-3% per month)	(i) Very high cost ($900-1300 kWh) (ii) Short life cycle due to deep discharge (iii) Require a special overcharge protection circuit
Lead acid	(i) Low cost (ii) Low self-discharge (2-5% per month)	(i) Short cycle life (1200-1800 cycles) (ii) Cycle life affected by depth of charge (iii) Low charge density (about 40 Wh/kg)
Nickel based	(i) Can be fully charged (3000 cycles) (ii) High energy density (50-80 Wh/kg)	(i) High cost, ten times that of lead acid (ii) High discharge (10% per month)
Sodium Sulphur (NaS)	(i) High efficiency (85-92%) (ii) High energy density (100 Wh/kg) (iii) No degradation for deep discharge	(i) Be heated in stand-by mode at 3250°C

Table 2. Summary of available battery technologies [14]

Type	LA	NiCd	NiMH	Li-ion	NaS	VRB
Energy density (Wh kg^{-1})	25-50	50-60	60-120	75-200	150-240	10-30
Power density (W kg^{-1})	75-300	~200	250-1000	500-2000	150-230	80-150
Cycle life (100% DOD)	200-1000	>1500	180-2000	1000-10,000	2500-4000	>12,000
Capital cost ($/kWh)	100-300	300-600	900-3500	300-2500	300-500	150-1000
Round-trip efficiency	75-85	70-75	65-80	85-97	75-90	75-90
Self-discharge	Low	High	High	Medium	-	Negligible

3. Mechanical Properties of Solar Batteries

In recent years, battery technology has emerged as a crucial enabler for reducing CO_2 emissions in global efforts to mitigate climate change. This condition is achieved through two primary pathways: enabling the transition to climate-neutral integrated energy systems, and separately supporting efficient renewable energy storage while displacing fossil fuels in vehicle propulsion systems [15]. Key Mechanical Features of Solar Batteries are as follows:

3.1 Casing or Enclosure

The battery casing should be constructed from materials resistant to impact, vibration, and temperature fluctuations. Additionally, it must be corrosion-resistant against battery acids and electrically insulated.

3.2 Temperature Resistance

Solar batteries must operate efficiently across a wide temperature range, from extreme cold to intense heat, without performance degradation. Typically, they should withstand temperatures ranging from -50°C to +150°C.

3.3 Strength and Durability

Solar batteries require high structural integrity to endure shocks and vibrations during transportation and installation.

3.4 Weight and Dimensions

Solar batteries should have an optimal weight and size for easy handling and installation. In this regard, lithium-ion batteries are preferred over lead-acid batteries due to their lighter weight and more compact design.

3.5 Long Lifespan

Battery lifespan is a crucial factor in selecting a solar battery. Lithium-ion batteries generally offer a longer service life compared to lead-acid batteries.

3.6 High Efficiency

Solar batteries must deliver high charge/discharge efficiency to minimize energy loss during these processes.

3.7 Low Self-Discharge Rate

This feature ensures that the battery loses minimal energy when in storage mode.

3.8 Depth of Discharge (DoD)

Batteries with a higher DoD can be discharged more deeply without sustaining damage.

3.9 Charge/Discharge Cycles

Solar batteries undergo continuous charging and discharging, and the number of these cycles significantly impacts their lifespan.

Table 3 summarizes the technological strengths and selected research opportunities in technology for some materials. The choice of materials in solar batteries directly impacts charge absorption, conduction, and storage. Lithium-ion batteries exhibit complex dynamics and thermal behavior. The mechanical analogy for battery dynamics is valuable due to its ability to provide accurate heat generation predictions while remaining intuitive to use, despite being a higher-order model. Additionally, because the system is modally decomposed, each degree of freedom can be analyzed independently, corresponding to different dynamic effects. The estimated heat is then applied to a lumped-mass thermal model to predict temperature. To determine the temperature profile of the cells under dynamic discharge conditions, the model was integrated with a lumped thermal system, as illustrated in Figure 2, where VQ represents the over potential voltage derived from the dynamic model. The dynamic model used to describe the dynamic response of a battery is shown in Figure 3[16]. Furthermore, in practice, solar modules never operate under conditions equal to the standard test conditions (STC) [17].

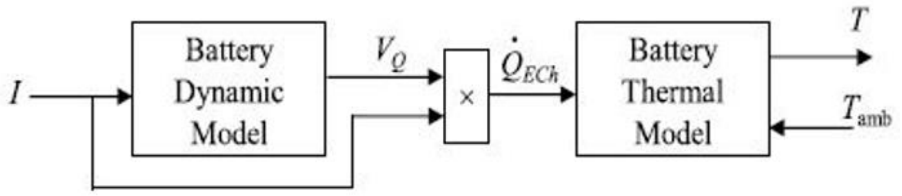


Figure 2. Thermo-mechanical coupled system [16]

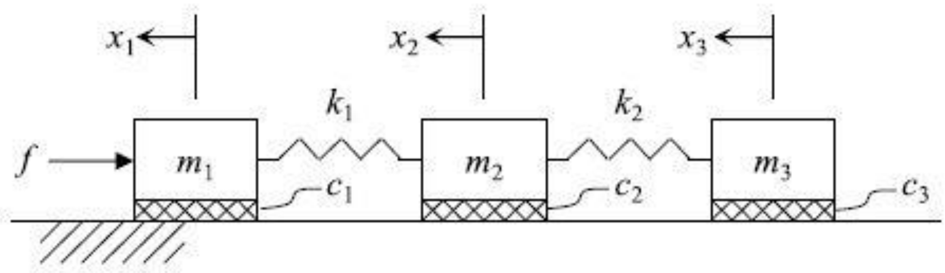


Figure 3. Three-degree-of-freedom damped spring-mass system analogy of a battery discharge dynamics [16]

The thermal analysis of lithium-ion batteries depends on precise thermal models. However, the electrochemical, electrical, and thermal fields interact with each other, creating a complex coupling effect during the charge/discharge process [18]. A battery dynamic and thermal model serves as a critical tool for analyzing and optimizing battery performance in applications such as electric vehicles (EVs). These models integrate electrical and thermal characteristics to predict battery behavior under diverse operating conditions, including fluctuations in current, voltage, and temperature. Different manufacturing techniques affect the structural integrity, conductivity, and overall efficiency of solar batteries. Some key methods include:

3.10 Roll-to-Roll Processing

This method allows for large-scale, cost-effective production of flexible solar cells. Studies have shown that roll-to-roll manufacturing enhances charge collection efficiency through uniform thin-film deposition [19].

3.11 Laser Scribing

Precision laser scribing reduces electrical losses in solar modules by creating well-defined conductive pathways. Research indicates that laser-scribed perovskite solar cells exhibit a 15% higher charging rate compared to traditional methods [20].

Table 3. Technology strengths and key research opportunities for photovoltaic materials. Materials are grouped by degree of technological development. Record cell and module efficiencies are indicated, based on certified measurements [17]

Material	Cell efficiency (%)	Module efficiency (%)	Technology strengths and options	Selected research/technology opportunities
Mature technologies deployed at a large scale				
Monocrystalline Si	25.6	22.4	Earth-abundant material >25-year track record	Further reduce recombination losses, in combination with new metallization schemes; improve light management in thinner wafers; improve IBC and SHJ cell designs.
Multicrystalline Si	21.3	18.5	Earth-abundant material >25-year track record	Improve water quality (minimize or passivate defects) to reduce recombination losses.
CIGS	21.7	17.5	Flexible substrates	Improve light management, increase efficiency for significant band gaps (tandem cells), reduce recombination losses, and enhance solution processing.
CdTe	21.5	18.6	Flexible substrates; short energy payback time	Reduce recombination losses by developing thinner cell designs that utilize light management.
Emerging technologies deployed on a smaller scale				
Dye-sensitized TiO_2	11.9	10.0	Tunable colors	Improve the redox couple, reduce recombination losses, increase the band gap, and enhance stability.
Thin-film Si	11.4	12.2	Flexible modules	Reduce recombination losses; improve light management.
Organic	11.5	9.5	Flexible modules, semitransparent modules	Improve light management, increase the band gap, enhance stability, and reduce recombination losses.
Technology at the manufacturing level				

Material	Cell efficiency (%)	Module efficiency (%)	Technology strengths and options	Selected research/technology opportunities
GaAs	28.8	24.1	Very high efficiency; flexible modules	Improve light management; develop IBC geometry; further develop thin-film multijunction cells by layer transfer.
Technologies under development				
Perovskite	21.0	n.a.	Solution processing; flexible modules	Reduce recombination losses, improve cell stability, avoid the use of Pb, increase efficiency for high-bandgap materials (random cells), and develop Si/Perovskite tandems.
CZTS	12.6	n.a.	Flexible modules	Reduce recombination losses; improve light management.

3.12 Screen Printing

Commonly used in silicon solar cells, screen printing affects the conductivity of the electrodes. However, if not optimized, it can lead to higher resistive losses, reducing charging efficiency.

4. Practical Testing

Several solar batteries were tested in the lab, each with unique specifications. The procedure was as follows:

(i) Measure the battery's open-circuit voltage using a Multimeter.

(ii) Connect the charge controller and record V_L Battery and V_{RL} Battery values.

(iii) Note the charge percentage displayed by the Aeca charge controller.

A sample charge controller and battery setup is shown in Figure 4. Since the focus is on charge percentage estimation, calculations for V_L Battery and VRL Battery have been omitted. The proposed method is as follows: After obtaining the open-circuit voltage, set the maximum charge to 13.7V and the minimum to 10V. The difference is *3.7V*, which is divided as:

1V = 27%

0.1V = 2.7%

Example Calculation for Battery *#1*:

Measured voltage: *12.56V*

Calculation:

$\Delta V = 12.56 - 10 = 2.56 \approx 2.5$

$2.56 = 2 + 0.5 = 27*2 + 2.7*5 = 67\%$

The formula can be summarized as follows:

Remaining Charge= $27*A+2.7*B$

$$RC = 27*A + 2.7*B \quad (2)$$

Where A and B represent the integer and decimal parts of the obtained difference, respectively, the results for six batteries are compared in Table 4, demonstrating close consistency between the charge controller's readings and the theoretical estimation. This approach provides a reliable approximation of the charge range.

Figure 5(a)-(b) compares the manual method with the automated process based on theoretical estimation. The ambient temperature was maintained at approximately 25°C.

The manufacturing process and the material composition of a solar battery significantly impact the charge rate parameter. These two factors play a crucial role in determining the efficiency of sunlight absorption, its conversion into electrical energy, and, consequently, the battery's charging speed.

Figure 4. Sample of battery (a) and charge controller (b)

There are specific characteristics that should be considered when evaluating a solar battery. These include the duration for which the solar battery can provide the required energy and the amount of energy it can supply. When considering solar energy storage options, one encounters many complex specifications.

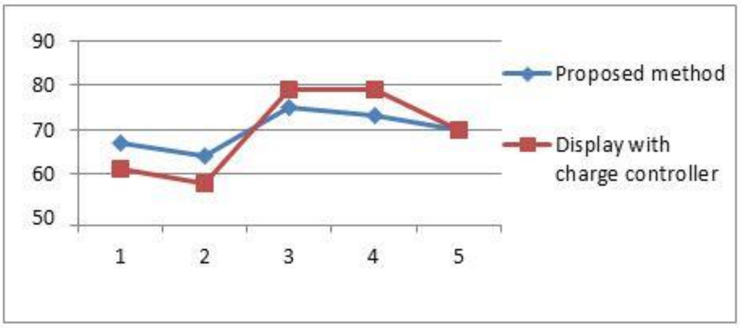
Key factors to consider during evaluation include battery capacity, depth of discharge (DoD), efficiency, warranty, and the manufacturer's reputation. Solar batteries, which play a vital role in energy storage for photovoltaic systems, must meet several critical mechanical requirements. These include the ability to withstand mechanical stresses such as bending or pressure during handling, installation, and operation. Structural integrity is crucial in preventing cracking or delamination, as these issues can lead to reduced efficiency and premature failure. Furthermore, the mechanical properties of battery components such as the casing, connectors, and internal structures significantly affect the overall reliability and lifespan of the solar battery. The manufacturing process and the resulting product quality are also crucial factors that determine the operational lifetime and durability of the final product. The influence of charging rate on the efficiency of the material/method is presented in Table 5.

Table 4. Comparison of two methods(T≈25°C)

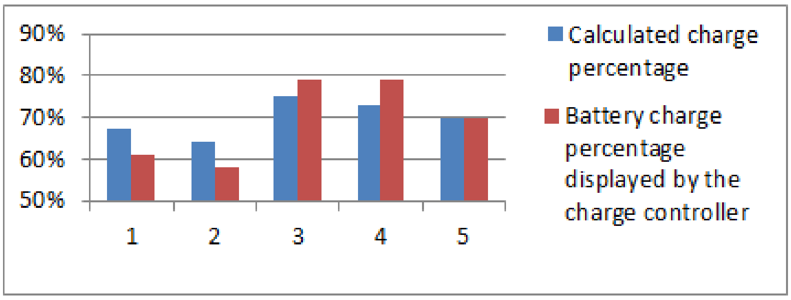
No. of Battery	Calculated Charge Percentage (%)	Battery Charge Percentage Displayed by the Charge Controller (%)
1 (Lead-acid)	67	61
2 (Lead-acid)	64	58
3 (Lead-acid)	75	79
4 (Lead-acid)	73	79
5 (Lead-acid)	70	70
6 (Lithium-ion)	89	90

Table 5. Charging rate impact on efficiency

Material/Method	Efficiency (%)	Charging rate impact
Monocrystalline silicon	20-22	High (fast charging)
Perovskite	25	Very high (rapid charge capture)
Cigs thin film	18-20	Moderate
Roll-to-roll manufacturing	-	Improves uniformity & efficiency
Laser scribing	-	Reduces resistance, faster charging



(a)



(b)

Figure 5. Comparison of two methods (a) and (b)

5. Conclusion

This study presents a practical methodology for estimating battery state of charge (SoC) that eliminates the need for complex charge controller modeling. The proposed technique offers a computationally efficient approximation for scenarios where precise measurements are inaccessible. Notably, the experimental results demonstrate strong agreement between the estimated and measured values, with deviations falling within an acceptable margin of error. This close correlation validates the reliability of the method while highlighting its potential for rapid field assessments.

The charging rate of solar batteries is highly dependent on the precision of manufacturing and the selection of materials. Advanced methods, such as laser scribing and roll-to-roll processing, combined with high-efficiency materials like perovskites and monocrystalline silicon, significantly enhance performance. Future innovations should focus on scalability, sustainability, and cost reduction to make solar energy more accessible and affordable.

6. Acknowledgment

The author gratefully acknowledges the Solar Energy Department at the Persian Gulf Specialized Center of Electrical and Electronics Engineering (Shiraz, Iran) for providing laboratory facilities and technical support essential for conducting this research. Their contribution was instrumental in enabling the experimental work presented in this study.

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