

ECE445
Senior Design Laboratory

DESIGN DOCUMENT

Photovoltaic Power Generation Charger

Team #51

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1. Introduction

1.1 Problem Statement

Portable charging in outdoor and off-grid scenarios still depends heavily on wall power or disposable batteries. This limitation is especially visible in small-scale applications such as camping, field sensing, emergency backup, and temporary device charging, where the user may have sunlight available but no stable grid source. A practical photovoltaic charger must therefore do more than simply connect a panel to a battery. The panel voltage changes with irradiance, temperature, and load, so direct connection causes low energy utilization, unstable charging current, and poor battery safety.

Our project addresses this problem by designing a compact photovoltaic power generation charger that can harvest solar energy, regulate the panel operating point, charge a rechargeable battery safely, and provide a regulated USB output for end devices. The system is intended as an off-grid DC charger rather than a grid-tied inverter. It focuses on four engineering goals: efficient solar energy extraction, stable closed-loop charging, safe battery handling, and clear user feedback. This direction is consistent with the emphasis on maximum power point tracking and front-end power regulation in photovoltaic power-conditioning literature [1].

1.2 Solution Overview and Visual Aid

The proposed system uses a nominal 18 V photovoltaic panel as the primary energy source. The panel output is measured by voltage and current sensing circuits and then processed by a microcontroller running a perturb-and-observe MPPT algorithm. The controller drives a synchronous buck charging stage so that the panel operates near its maximum power point while the battery is charged using a constant-current and constant-voltage profile. A protected 2S Li-ion battery pack provides energy buffering, and a regulated 5 V USB stage powers external electronic devices even when irradiance varies rapidly. The same controller also handles thermal protection, overcurrent shutdown, status display, and fault indication.

Figure 1 illustrates the intended use context. Sunlight is captured by the photovoltaic panel, processed by the charger, stored in a rechargeable battery, and finally delivered to either a USB load or a battery-backed device. This creates a complete renewable-energy-based charging path from source to end use.

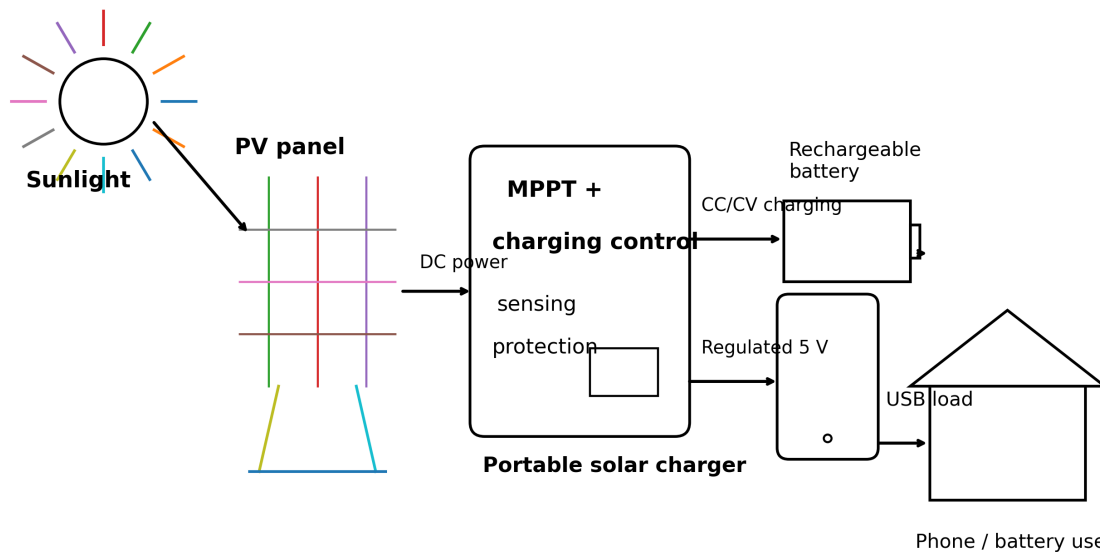


Figure 1: Visual aid of the photovoltaic power generation charger in use.

1.3 High-Level Requirements List

The photovoltaic power generation charger shall satisfy the following high-level requirements.

- (1) **Solar energy harvesting performance:** When the panel input varies between 14 V and 22 V, the system shall track at least 95% of the available maximum panel power within 1.0 s after a step irradiance change, and the main charging converter shall maintain at least 88% efficiency at a 10 W to 20 W output level.
- (2) **Battery charging quality:** The charger shall implement a CC/CV profile for a 2S Li-ion battery pack with charge current up to 1.5 A and final charge voltage of 8.40 ± 0.05 V. Charging shall stop when the battery temperature exceeds 45°C and shall only resume after the temperature falls below 40°C .
- (3) **Output regulation and safety:** The system shall provide a 5 V USB output of 5.0 ± 0.25 V at up to 2 A continuous current, update user-visible status information at no less than 2 Hz, and enter a latched fault state within 20 ms under short-circuit, reverse-polarity, or severe overcurrent conditions.

2. Design

2.1 Block Diagram

The system is divided into five interacting modules: photovoltaic input, sensing, power conversion, battery and load path, and controller/protection. The controller is the coordination center. It receives sampled panel and battery data, computes the MPPT and charging commands, drives the main PWM stage, monitors fault conditions, and updates the user interface.

Group 51 Photovoltaic Power Generation Charger - System Block Diagram

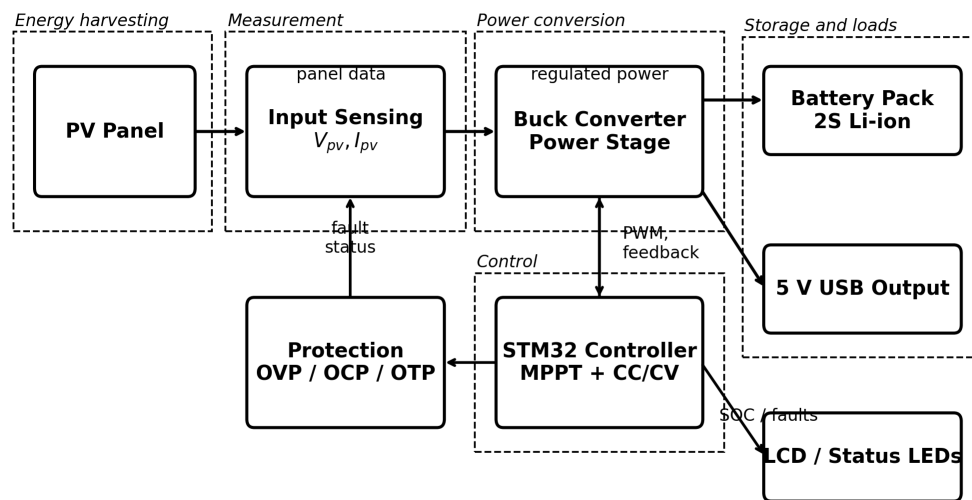


Figure 2: System block diagram for the photovoltaic power generation charger.

The photovoltaic input subsystem delivers raw DC power. The sensing subsystem converts electrical variables into ADC-compatible signals. The buck conversion stage performs the energy transfer from panel to battery. The battery and output subsystem stores energy and supplies the USB load. The monitoring and protection subsystem supervises all operating states and can override the converter when a fault is detected.

2.2 Photovoltaic Input and Sensing Subsystem

This subsystem contains the solar panel interface, input filter, reverse-current blocking path, current shunt, and voltage sensing network. Its role is to provide accurate, low-noise measurements of V_{pv} and I_{pv} while protecting the panel and downstream converter during transients and misconnection events. The controller depends on this subsystem because the MPPT algorithm uses real-time

panel power, $P_{pv} = V_{pv}I_{pv}$, as its objective variable. If sensing is noisy or biased, the operating point will shift away from the true maximum power point.

A fuse is placed near the panel input to protect against catastrophic shorts. A reverse-blocking MOSFET prevents battery energy from discharging back into the panel at night. A resistor-divider network scales the panel voltage into the ADC range. A low-value shunt resistor and current-sense amplifier measure panel current. RC filtering is added so that the measurement bandwidth is fast enough for control but slow enough to reject switching ripple.

Table 1: Photovoltaic input and sensing subsystem requirements and verifications.

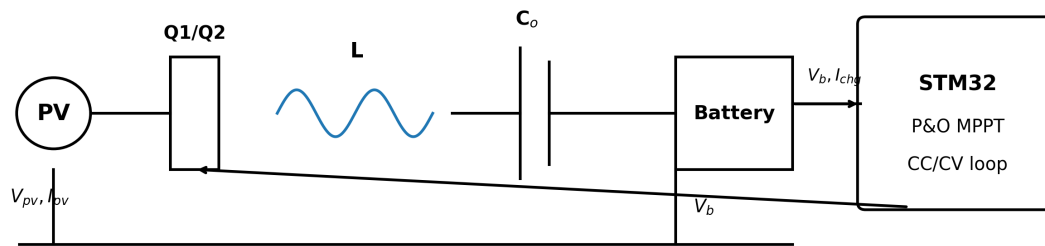
Requirement	Verification Procedure and Success Criterion
Panel voltage measurement error shall be within $\pm 2\%$ over a 14 V to 22 V input range.	Apply five calibrated DC input points using a programmable supply and compare the ADC-reported panel voltage with a benchtop DMM. The subsystem passes if the maximum absolute error is no more than 2% at all five points.
Panel current measurement error shall be within $\pm 3\%$ for 0.2 A to 2.0 A.	Inject known current through the shunt path using an electronic load and laboratory supply. The subsystem passes if the measured current differs from the reference meter by no more than 3% across the test range.
Reverse leakage from battery to panel shall remain below 10 mA when the panel voltage falls below the battery voltage.	Set the panel-side source to 0 V while the battery emulator is held at 7.4 V to 8.4 V. Measure reverse current with an ammeter. The subsystem passes if leakage stays below 10 mA in all tested battery states.

2.3 Power Conversion and MPPT Control Subsystem

The power conversion subsystem is the main student-designed circuit in this project. It uses a synchronous buck converter controlled by an STM32 microcontroller. The controller runs two loops. The outer logic is a perturb-and-observe MPPT routine that updates the panel operating point. The inner charging loop enforces the battery-side current or voltage target depending on the state of charge. This architecture is practical for a student prototype because it preserves a clear energy path, keeps the switching network manageable, and follows the broader photovoltaic design principle that the front-end DC/DC stage should regulate the panel operating point while the rest of the system enforces load-side constraints [1].

Figure 3 shows the simplified converter concept used in this project. The controller senses both panel-side and battery-side variables. It modulates the gate signals of the buck stage to balance three objectives: maximizing harvested power, respecting the battery charge profile, and staying within thermal and electrical safety limits.

Simplified MPPT charging power stage



Power stage sized so current ripple stays below charging-loop limit

Figure 3: Simplified MPPT charging power stage.

The planned nominal operating point is a 50 W, 18 V panel charging a 2S Li-ion battery. The switching frequency is selected as 100 kHz to reduce inductor size without making gate drive and loss management overly difficult for a first prototype. The nominal inductor value is 150 μ H. This choice is supported by the tolerance analysis in Section 2.7.

Table 2: Power conversion and MPPT subsystem requirements and verifications.

Requirement	Verification Procedure and Success Criterion
The MPPT algorithm shall reach at least 95% of the available maximum panel power within 1.0 s after a step change in simulated irradiance.	Use a programmable DC source or solar panel emulator with two operating conditions representing an irradiance step. Record V_{pv} and I_{pv} before and after the step. The subsystem passes if the steady-state power after 1.0 s is at least 95% of the emulator's reference peak-power value.
The buck stage shall achieve at least 88% electrical efficiency for 10 W, 15 W, and 20 W operating points.	Measure input power from the panel emulator and output power into the battery emulator. The subsystem passes if $\eta = P_{out}/P_{in} \geq 88\%$ at each operating point.
The inductor ripple current shall remain below 0.5 A over the 14 V to 22 V panel-voltage range.	Measure inductor current with a current probe or infer ripple from shunt waveform under three panel voltages and two battery states. The subsystem passes if peak-to-peak ripple stays below 0.5 A in all cases.

2.4 Battery Management and Output Subsystem

The battery and load subsystem stores harvested energy and supplies the end user with a stable output. A 2S Li-ion battery pack is selected because it offers higher energy density than lead-acid alternatives while keeping the charging voltage at a manageable level. The battery path includes a

protection board that monitors cell overvoltage, undervoltage, and severe overcurrent. On the user side, a dedicated 5 V output regulator converts battery energy into a USB-compatible supply for a phone, microcontroller board, or other portable electronic load.

This subsystem must interact cleanly with the charging converter. During high irradiance, the panel can charge the battery and support the load simultaneously. During low irradiance or transient cloud cover, the battery supplies the USB output so that the user does not see severe droop or intermittent resets. This energy-buffering function is one of the main reasons for including a rechargeable battery rather than driving the USB output directly from the panel.

Table 3: Battery management and output subsystem requirements and verifications.

Requirement	Verification Procedure and Success Criterion
The battery charging profile shall provide a constant-current phase of 1.5 ± 0.1 A followed by a constant-voltage phase of 8.40 ± 0.05 V.	Charge a battery emulator and then a protected battery pack while logging current and voltage. The subsystem passes if the current-regulated phase remains within the stated current band and the transition to CV occurs at 8.40 ± 0.05 V.
The USB output shall remain within 5.0 ± 0.25 V from no load to 2 A load.	Sweep the load current using an electronic load from 0 A to 2 A in 0.25 A steps. The subsystem passes if the output voltage remains between 4.75 V and 5.25 V at all steps.
With panel input removed, the system shall support a 1 A USB load for at least 30 minutes from a fully charged battery pack.	Fully charge the battery pack, disconnect panel input, and apply a 1 A constant-current USB load. The subsystem passes if the load remains regulated for at least 30 minutes without triggering undervoltage shutdown.

2.5 Monitoring, Protection, and User Interface Subsystem

The monitoring subsystem exists to make the charger usable and safe. It measures battery temperature, tracks state variables such as input power, charging mode, and USB status, and displays essential information on a small LCD with LED fault indicators. This subsystem also implements the protection policy. It can disable PWM output when a short circuit, reverse input, thermal fault, or persistent overcurrent condition is detected.

Protection has to override convenience. For that reason, the fault logic is designed as a latched state rather than an automatic immediate restart. After a major fault, the user must clear the fault and restore safe operating conditions before charging resumes. This reduces the chance of oscillatory fault-retry behavior, which is undesirable in a battery charging system.

Table 4: Monitoring, protection, and user-interface subsystem requirements and verifications.

Requirement	Verification Procedure and Success Criterion
The displayed input voltage, battery voltage, and charging state shall refresh at least 2 times per second.	Log consecutive display updates or serial debug timestamps during charging. The subsystem passes if the average refresh rate is 2 Hz or higher over a 60 s window.
The controller shall shut down the converter within 20 ms after a hard output short or severe overcurrent event.	Trigger a controlled short through an electronic protection fixture while observing the PWM gate signal and current waveform on an oscilloscope. The subsystem passes if gate shutdown occurs within 20 ms.
Charging shall stop when the battery temperature exceeds 45°C and shall not resume until the sensed temperature falls below 40°C.	Inject simulated NTC values or heat the battery sensor in a controlled environment. The subsystem passes if charging stops at $45 \pm 2^\circ\text{C}$ and restart is inhibited until temperature is below $40 \pm 2^\circ\text{C}$.

2.6 Physical Implementation and Integration

The current implementation plan uses a two-board approach. The power board contains the buck converter, current shunt, protection path, battery connector, and USB output regulator. The control board contains the STM32, ADC front-end, LCD header, buttons, and low-power logic. Separating the boards simplifies routing and reduces the risk that switching noise will corrupt measurement traces.

The enclosure will expose only the solar input connector, USB output, power switch, and display. High-current nodes, inductor terminals, and battery wiring will remain inside the enclosure. The panel input and battery input will be keyed to reduce reverse connection. Heat-generating components such as MOSFETs and the inductor will be placed near ventilation openings and thermal copper pours. The final prototype is expected to operate at desk scale and demonstrate the complete power path rather than maximize absolute power density.

2.7 Tolerance Analysis

The most critical function of the charger is stable power transfer from the photovoltaic panel to the battery while preserving a valid MPPT signal and a safe charging current. If the buck-stage ripple current becomes too large, the sensed panel power will fluctuate excessively, the MPPT algorithm may dither around the wrong operating point, and the battery current can violate its intended limit. We therefore use the inductor ripple current as the key tolerance-analysis target.

For an ideal buck converter,

$$D \approx \frac{V_b}{V_{pv}} \quad (1)$$

and the peak-to-peak inductor ripple current is

$$\Delta I_L = \frac{(V_{pv} - V_b)D}{Lf_s}, \quad (2)$$

where V_{pv} is panel voltage, V_b is battery voltage, L is the main inductor, and f_s is the switching frequency [2]. The output-voltage ripple can be approximated as

$$\Delta V_o \approx \frac{\Delta I_L}{8C_o f_s} + \text{ESR} \cdot \Delta I_L. \quad (3)$$

For this design we use the following nominal values:

$$V_b = 8.4 \text{ V}, \quad L = 150 \text{ } \mu\text{H}, \quad f_s = 100 \text{ kHz}, \quad C_o = 220 \text{ } \mu\text{F}.$$

To include real component spread, we assume an inductor tolerance of $\pm 20\%$ and a switching-frequency tolerance of $\pm 5\%$. Figure 4 shows the predicted ripple-current envelope from 14 V to 22 V panel voltage.

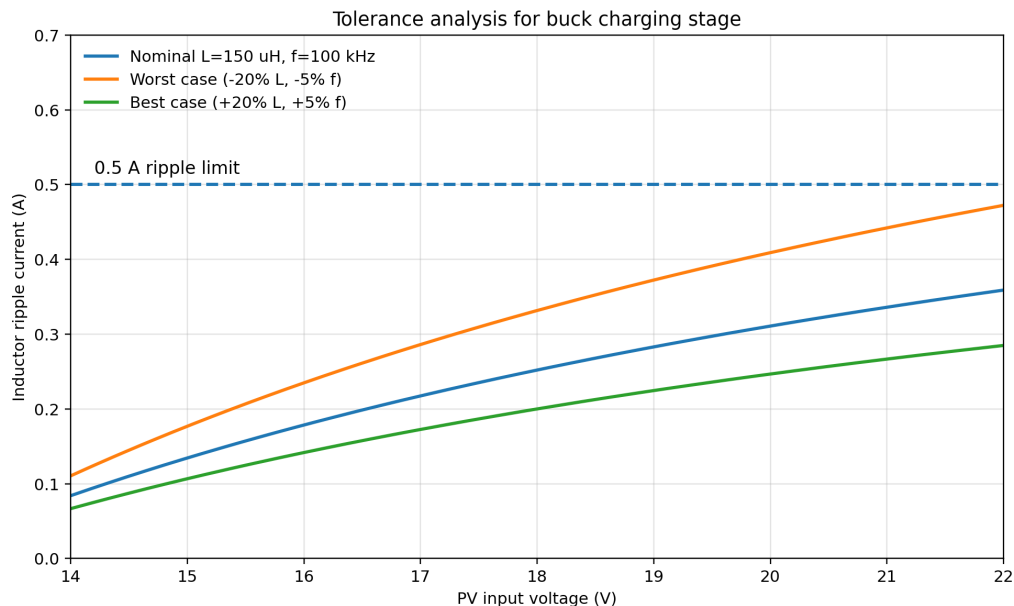


Figure 4: Predicted inductor ripple current under nominal and tolerance-bounded conditions.

The worst case occurs near the highest panel voltage, with $L = 120 \text{ } \mu\text{H}$ and $f_s = 95 \text{ kHz}$. Substituting $V_{pv} = 22 \text{ V}$ and $V_b = 8.4 \text{ V}$ into (1) and (2) gives

$$D \approx \frac{8.4}{22} = 0.382,$$

$$\Delta I_L \approx \frac{(22 - 8.4)(0.382)}{(120 \times 10^{-6})(95 \times 10^3)} \approx 0.456 \text{ A}.$$

This remains below the design limit of 0.5 A, so the converter still satisfies the ripple-current requirement. Using (3) with $C_o = 220 \mu\text{F}$ and a conservative capacitor ESR of $30 \text{ m}\Omega$ gives

$$\Delta V_o \approx \frac{0.456}{8(220 \times 10^{-6})(95 \times 10^3)} + 0.03(0.456) \approx 16.4 \text{ mV}.$$

This voltage ripple is small relative to the 8.4 V battery target. Therefore, the selected values provide enough tolerance margin for stable charging-loop operation, accurate MPPT power estimation, and safe battery current regulation. This analysis demonstrates that the critical converter function is feasible before full hardware integration.

3. Cost

Table 5 lists the estimated material cost for one prototype. Prices are approximate and reflect typical retail quantities rather than large-volume sourcing.

Table 5: Estimated bill of materials for one prototype.

Part	Qty.	Unit Cost (USD)	Total (USD)	Notes
18 V, 50 W photovoltaic panel	1	48	48	Main energy source
STM32 development board or MCU board	1	18	18	Control and UI
Power MOSFETs and gate driver	1 set	16	16	Main buck stage
150 μH inductor and output capacitor set	1 set	14	14	Power stage passives
Current-sense amplifier, shunt, and voltage-divider parts	1 set	10	10	Input and charge sensing
2S Li-ion battery pack	1	24	24	Energy storage
2S battery protection board	1	9	9	Battery safety
5 V USB output regulator and connector parts	1 set	12	12	Load output
LCD and status LEDs	1 set	8	8	User interface
PCB fabrication and prototyping material	1 set	32	32	Board fabrication and headers
Enclosure, connectors, fuse, switches, wiring	1 set	26	26	Mechanical and safety items
Heat sink and thermal interface material	1 set	11	11	Thermal management
Miscellaneous spare components	1 set	20	20	Rework margin
Estimated total			248	

4. Schedule

The remaining schedule is organized by week and by team member so that every week has a concrete task assignment, consistent with the course design-document expectations.

Table 6: Group 51 implementation schedule.

Week	Guangjun Xu	Sunhao Zhang	Xu Li
04/06	Finalize system architecture, define firmware states, and prepare ADC/PWM software framework.	Finalize buck-stage schematic, component values, and safety-protection path.	Finalize battery path, USB output stage, display wiring, and enclosure interface.
04/13	Implement MPPT routine and serial-debug logging on STM32.	Assemble sensing and power-stage prototype on bench hardware.	Assemble battery-monitoring, temperature-sensing, and LCD prototype.
04/20	Integrate CC/CV charging loop with MPPT arbitration logic.	Bench-test power-stage efficiency, ripple, and start-up behavior.	Validate USB regulation and battery protection thresholds.
04/27	Integrate fault handling, display update logic, and data logging.	Revise hardware layout based on bench-test results and thermal observations.	Build enclosure, connector layout, and user-interface panel.
05/04	Run end-to-end solar-emulator tests and tune firmware parameters.	Complete full hardware integration and verify charging-path stability.	Complete integrated battery and USB load testing; document measured results.
05/11	Prepare final demo script, system validation tables, and presentation material.	Prepare final hardware assembly, safety checklist, and spare test setup.	Prepare final user guide, cost update, and poster/document formatting support.

5. Ethics and Safety

5.1 Ethics

The team will follow the IEEE Code of Ethics in both design and reporting [3]. This means we will make engineering decisions that prioritize public safety, present measured performance honestly,

acknowledge limitations, and document failures rather than hiding them. In a power-electronics project, exaggerated performance claims can be dangerous because they may cause a user to trust an unsafe charger or misuse a battery pack. We therefore commit to reporting efficiency, charging current, and protection behavior only after measurement under stated test conditions.

We also consider environmental responsibility. The project is motivated by renewable energy use, but renewable branding does not automatically make a design ethical. Battery cells, power semiconductors, and enclosures still have material cost and disposal impact. For that reason, the design emphasizes rechargeable storage, low standby loss, reusable hardware, and responsible end-of-life handling of battery packs.

5.2 Safety

The main hazards in this project are electrical overstress, battery misuse, thermal rise, and incorrect user connection. To address these risks, the hardware includes a fuse, reverse-blocking input path, overcurrent shutdown, thermal cut-off, protected battery pack, and a latched fault state that prevents uncontrolled automatic restart. The enclosure is designed so that the user cannot touch high-current nodes during normal operation.

Although this project is a student prototype and is not being submitted for certification, its design decisions are informed by standards relevant to photovoltaic hardware and power converters. The photovoltaic module selection and handling are aligned with the intent of IEC 61215 and IEC 61730, while the converter safety approach follows the intent of IEC 62109-1 [4, 5, 6]. These references support our decisions on electrical isolation awareness, fault containment, thermal management, and safe user interaction.

References

References

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