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By

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Topic

**Design Optimization and Sustainability Assessment of Solar
Powered Charging Systems for Shared Electric Scooters: A Case
study of the University of El Oued, Algeria**

In May 2026 in front of the jury committee:

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Abstract

The adoption of flexible mobility solutions offers significant social and environmental benefits, particularly for low-income users in regions with harsh desert climates. However, achieving a sustainable transition away from fossil fuel–dependent energy systems require overcoming several technical and economic challenges. Addressing these barriers is essential for advancing green mobility powered by decentralized renewable energy solutions, such as solar photovoltaic systems.

This thesis aims to investigate the design and optimization of a solar-powered charging infrastructure for shared e-scooter fleets on university campuses in arid regions. Focusing on El Oued, the study evaluates the techno-economic feasibility and socio-environmental impacts of the proposed energy system that includes grid connected rooftop PV modules, batteries, and electric scooters. Different charging and storage configurations were analysed to identify the most reliable and cost-effective solution. To ensure practical relevance, technical findings were complemented by a student survey examining user behaviour and acceptance of shared e-mobility services. Results indicate that a 50/50 optimized cycling strategy combined with lithium-ion battery storage provides the best balance between performance, reliability, and cost. The proposed framework offers a scalable approach for integrating renewable energy into campus mobility systems, supporting Green Campus initiatives and reducing transportation-related carbon emissions.

Key words: Sustainable mobility, Solar PV, Shared E-scooters, Techno-economic assessment, Optimization, University of El Oued, Smart Campus.

الملخص:

يوفر اعتماد حلول التنقل المرنة فوائد اجتماعية وبيئية كبيرة، خاصة للمستخدمين ذوي الدخل المنخفض في المناطق ذات المناخات الصحراوية القاسية. ومع ذلك، فإن تحقيق انتقال مستدام بعيداً عن أنظمة الطاقة المعتمدة على الوقود الأحفوري يتطلب تجاوز عدة تحديات تقنية واقتصادية. معالجة هذه الحواجز أمر أساسي لتعزيز التنقل الأخضر المدعوم من حلول الطاقة المتجددة اللامركزية، مثل أنظمة الطاقة الشمسية الكهروضوئية. تهدف هذه الرسالة إلى دراسة تصميم وتحسين بنية تحتية للشحن تعمل بالطاقة الشمسية لأساطيل السكوترات الكهربائية المشتركة في الجامعات في المناطق الجافة. تركز الدراسة على الواد، حيث تقيم الجدوى التكنولوجية والاقتصادية والتأثيرات الاجتماعية والبيئية لنظام الطاقة المقترح الذي يشمل وحدات الطاقة الشمسية المتصلة بالشبكة على الأسطح، والبطاريات، والسكوتر الكهربائي. تم تحليل تكوينات الشحن والتخزين المختلفة لتحديد الحل الأكثر موثوقية وفعالية من حيث التكلفة. لضمان الصلة العملية، تم تعزيز النتائج الفنية باستطلاع طلابي فحص سلوك المستخدمين وقبولهم لخدمات التنقل الإلكتروني المشتركة. تشير النتائج إلى أن استراتيجية دورة محسنة بنسبة 50/50 مع تخزين بطاريات الليثيوم أيون توفر أفضل توازن بين الأداء والموثوقية والتكلفة. يقدم الإطار المقترح نهجاً قابلاً للتوسع لدمج الطاقة المتجددة في أنظمة التنقل الجامعي، ودعم مبادرات الحرم الجامعي الأخضر وتقليل انبعاثات الكربون المرتبطة بالتنقل.

الكلمات المفتاحية: التنقل المستدام، الخلايا الكهروضوئية، السكوترات الكهربائية التشاركية، التقييم التقني الاقتصادي، التحسين، جامعة الوادي، الحرم الجامعي الذكي.

Dedicated to

MY PARENTS

MY FAMILY

MY COLLEGES

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Nomenclature

AC	Alternating Current
BESS	Battery Energy Storage System
BMS	Battery Management System
CAPEX	Capital Expenditure
CO ₂	Carbon Dioxide
COE	Cost of Energy
CRF	Capital Recovery Factor
DC	Direct Current
DoD	Depth of Discharge
EMS	Energy Management Strategy
EV	Electric Vehicle
GHI	Global Horizontal Irradiance
HES	Hybrid Energy System
LCOE	Levelized Cost of Energy
Li-ion	Lithium-ion
MPPT	Maximum Power Point Tracking
NOCT	Nominal Operating Cell Temperature
NPC	Net Present Cost
O&M	Operation and Maintenance
OPEX	Operational Expenditure
PV	Photovoltaic
RF	Renewable Fraction
SoC	State of Charge
STC	Standard Test Conditions

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General Introduction

Global Context and the Rise of E-mobility

The world is currently facing an unprecedented environmental crisis driven by greenhouse gas emissions, with the transportation sector being a primary contributor. To combat climate change and reduce dependence on fossil fuels, the global community has pivoted toward sustainable mobility solutions. Electric mobility (E-mobility), particularly micro-mobility solutions like electric scooters (e-scooters), offer a promising path for reducing the carbon footprint of urban transportation [1]. E-scooters are efficient for short-distance travel and "last-mile" connectivity, making them increasingly popular in dense urban areas and educational campuses [2].

Solar Energy Potential in Algeria

Algeria, the largest country in Africa, possesses one of the highest solar potentials in the world, with an average horizontal irradiance exceeding 6.5 kWh/m²/day in its southern regions [3]. Under the National Renewable Energy Program, Algeria aims to achieve 22 GW of renewable capacity by 2035 [4]. Leveraging this solar abundance to power electric vehicle charging infrastructure is a strategic step toward energy independence and decarbonization [5]. In desert regions like El Oued, solar photovoltaics (PV) represent the most viable and sustainable energy source for autonomous and grid-connected charging systems.

Problem Statement: Charging Challenges at the University of El Oued

The University of El Oued, with its expansive campus and the growing use of electric scooters among students and staff, requires a reliable charging infrastructure. Currently, most electric scooters are charged via the national grid, which is largely powered by natural gas. This grid dependency reduces the environmental benefits of electric mobility and increases the operational costs for the university. Furthermore, the extreme desert climate and high temperatures in El Oued pose technical challenges for PV efficiency and battery storage life, necessitating an optimized design for maximum reliability and cost-effectiveness.

Research Aim and Objectives

The aim of this study is to design, optimize, and assess the sustainability of a solar-powered charging system for a shared e-scooter fleet at the University of El Oued. The main objectives include:

- Modelling the energy demand for an e-scooter fleet based on typical campus mobility patterns.

- Performing a techno-economic optimization of the PV-battery system using key performance indicators such as Net Present Cost (NPC) and Levelized Cost of Electricity (LCOE).
- Evaluating the environmental impact through CO₂ emission reduction calculations.
- Assessing the social and economic dimensions of sustainability to ensure practical applicability in the Algerian context.

Thesis Structure

This thesis is organized into three main chapters. **Chapter 1** provides a comprehensive literature review on sustainable mobility, PV-powered charging technologies, and optimization methods. **Chapter 2** details the methodology, including solar resource analysis, demand modelling, and the techno-economic framework. **Chapter 3** presents the simulation results, case study analysis, and discussion of the findings, followed by a general conclusion and recommendations for future research.

CHAPTER 01:

Literature Review

Chapter 1. Literature Review

1. Introduction

Driven by the urgent transition toward green mobility in arid and semi-arid environments, academic research has increasingly focused on the intersection between renewable energy expansion and sustainable transportation infrastructure. This literature review synthesizes the current state of knowledge regarding electric mobility (e-Mobility), the grid constraints associated with vehicle charging, and the deployment of solar photovoltaic (PV) systems to decarbonize localized transport networks. By evaluating international empirical studies, technical evaluations, and regional assessments, this section establishes the scientific and technological foundation for integrating PV infrastructure with electric scooter (e-scooter) charging hubs. Significant attention is directed towards the Algerian context, highlighting how the unique solar irradiance patterns and urban characteristics of El Oued Province offer special potential and localised challenges for the implementation of sustainable micro-mobility.

2. E-mobility: State of the art

Global mandates to curb greenhouse gas emissions have forced nations to embed sustainable transport paradigms directly into their core energy strategies. In arid regions such as Algeria, electric micro-mobility primarily represented by shared e-scooter fleets has emerged as a pragmatic alternative for university campuses due to low operational maintenance, high energy efficiency, and high flexibility [6]. These compact transport systems target "last-mile" travel deficits by eliminating direct tailpipe emissions, offering a cleaner substitute for the fossil-fuel-dependent motorcycles and cars that dominate academic environments.

However, scaling up an e-scooter network introduces immediate complications, chiefly the sudden addition of a substantial electrical load onto local distribution systems to replenish battery cells. Relying entirely on national power grids to meet this charging demand spikes institutional electricity expenses and, worse, ties the environmental benefits of electric transport back to fossil-fuel-dominated power plants. Consequently, decoupling micro-mobility from conventional, carbon-heavy electricity sources through solar-integrated charging stations remains essential to building a genuinely sustainable transport ecosystem.

3. Solar Photovoltaic Systems: State of the art

Modern solar photovoltaic (PV) technology has shifted from basic central generation toward decentralized, highly efficient power hubs tailored for specific, localized loads [7]. Recent advancements focus heavily on system survivability and yield optimization under extreme weather conditions, where high ambient temperatures and dust directly degrade performance. In the Algerian Sahara, extensive field research confirms that deploying bifacial modules and high-temperature-resistant cell materials helps counteract the thermal degradation caused by intense solar exposure [8].

Furthermore, integrating advanced Energy Storage Systems (ESS), such as lithium-ion batteries, alongside smart power controllers is now a standard requirement to stabilize the power supply against the natural intermittency of solar resources [6]. To balance technical reliability with financial viability, researchers frequently rely on techno-economic optimization frameworks [9]. This comprehensive engineering approach ensures that decentralized solar infrastructures can sustainably support local urban transit and green mobility projects over the long term [10].

4. Integration of PV Systems for E-Scooter Charging: Global Trends and Case Studies

The global adoption of micro-mobility programs, especially shared e-scooters, has proven highly effective at resolving "last-mile" transit bottlenecks across sprawling university campuses and urban centers [6]. To secure the environmental integrity of these programs, recent academic efforts emphasize powering the docking infrastructure directly with solar PV arrays [8]. Because e-scooters have modest energy configurations compared to full-sized electric cars, building decentralized, solar-powered charging stations whether operating completely off-grid or tied to the local network is highly feasible for educational institutions.

Empirical data from the Mediterranean and Middle east and north Africa (MENA) regions demonstrate that solar-driven charging hubs can achieve high energy self-sufficiency while dropping the carbon footprint of campus travel to near zero. Beyond engineering metrics, case studies reveal a dual psychological benefit: these solar stations relieve the university's primary electrical infrastructure during peak hours while acting as highly visible symbols of sustainability that encourage students to adopt eco-friendly commuting habits [11].

4.1. Technical Feasibility of Solar-Powered Micro-mobility

The operational success of PV-driven charging stations depends heavily on the real-time interaction between regional solar profiles, local climate variables, and user demand patterns. Technical viability is proven by mathematically modelling the total energy consumption of the scooter fleet against the hourly solar irradiance curves of the target site. For institutions like the University of El Oued, campus activity and charging demands peak during daylight hours (8:00 AM to 5:00 PM), aligning almost perfectly with peak solar generation. This natural synchronization minimizes the need for massive, expensive battery storage banks, improving the project's overall cost-effectiveness and simplifying long-term maintenance.

4.2. Technical and Economic Challenges of PV-Powered Charging Systems

Deploying solar charging stations for e-scooters requires overcoming a complex matrix of engineering and financial hurdles, particularly in desert university environments.

4.2.1 Technical Challenges: Intermittency and Energy Management

The most significant technical hurdle is the intermittent nature of solar energy. PV generation is dependent on weather conditions and daylight hours, while charging demand may occur at any time. This mismatch requires:

- **Energy Storage Systems (ESS):** The need for high-capacity batteries to store surplus energy. However, managing the energy transfer between the station's storage and the scooter's internal battery involves conversion losses.
- **System Efficiency:** Losses in DC/AC inverters and power controllers can reduce the overall performance. In hot climates like the Algerian Sahara, high temperatures (exceeding 40°C) lead to a decrease in PV panel efficiency and faster degradation of battery cells [9].

4.2.2 Economic Challenges: Investment and Maintenance

From an economic perspective, although the price of PV panels has declined globally, the Levelized Cost of Energy (LCOE) for a standalone charging station can still be high due to:

- **Capital Expenditure (CAPEX):** The initial cost of high-quality PV modules, batteries, and smart charging docks is significant [12].
- **Operating Expenditure (OPEX):** Maintenance in desert environments is more costly. "Soiling" (dust and sand accumulation) requires frequent cleaning to prevent drastic drops

in energy yield. Without a proper maintenance plan, the "Payback Period" of the project could be significantly extended.

5. State of the art of Sharing Economy in E-mobility

The sharing economy has altered modern urban transit through the concept of "Mobility as a Service" (MaaS), moving communities away from individual vehicle ownership toward shared asset utilization. Applying this model to campus e-mobility optimizes the physical footprint of charging docks, lowers transit costs for individual students, and reduces the total volume of vehicles required on site [12]. Academic evaluations indicate that functional sharing models rely on a reliable network of physical docking hubs coupled with an intuitive digital application for booking and tracking [13]. Within university campuses, this shared architecture minimizes parking congestion while fostering a collective sense of environmental and civic responsibility among users.

6. Solar Photovoltaic Systems and E-mobility in Algeria

Algeria holds one of the most substantial solar resource potentials globally, with a national average Global Horizontal Irradiance (GHI) exceeding 5.5 kWh/m²/day. This resource deepens in southern desert regions like El Oued, Ouargla, and Adrar, which receive over 6.5 kWh/m²/day and experience more than 3,500 hours of clear sunshine annually [12]. This vast solar wealth creates an ideal setting for deploying decentralized PV technologies across public and urban infrastructures.

Financially, this potential is supported by a massive 80% global reduction in the Levelized Cost of Energy (LCOE) for solar PV over the past decade, driven by manufacturing innovations and market scaling. For energy-intensive sectors like transportation, this cost reduction transforms solar power into a highly competitive option for campus-focused charging networks [12].

To capitalize on this resource, the Algerian government's national energy policy targets 22 GW of installed renewable energy capacity by 2035. The National Renewable Energy Program explicitly focuses on integrating green energy across public services, education, and transport systems to diversify the national energy mix [12]. Implementing decentralized PV charging infrastructures matches this political mandate, offering a stable power supply for campus e-scooters without straining local distribution grids or inflating university utility bills.

7. Challenges and Opportunities for solar charging shared e-mobility systems in Algeria

The transition toward sustainable transportation in Algeria, particularly through solar-powered micro-mobility, represents a strategic intersection between national energy goals and local environmental needs. While the geographical and climatic conditions of regions like El Oued offer a fertile ground for such innovations, the practical deployment of these systems is not without its complexities. This section provides a comprehensive analysis of the multi-dimensional factors ranging from regulatory frameworks to environmental constraints that define the landscape for shared e-mobility in the Algerian context. By evaluating both the hurdles and the potential gains, we can better understand the feasibility of transforming university campuses into hubs for green energy and sustainable transition. Here, a political, economic, social and technical (PEST) framework is adopted to identify challenges and opportunities. This approach is vital to understand the local context and suggest appropriate strategies and solutions.

7.1. Challenges for solar charging shared e-mobility systems in Algeria

Implementing solar-powered charging infrastructure for shared e-scooters in Algeria involves navigating a variety of complex hurdles. These challenges, which range from environmental constraints to technical, economic, and social factors, represent the primary barriers that could affect the efficiency and scalability of such sustainable initiatives within the local context.

- **Political challenges**

The primary obstacle is the complete absence of a dedicated legal framework governing electric micro-mobility on public roads and within institutional domains. Current Algerian traffic legislation lacks clear classifications for e-scooters, creating legal ambiguity regarding user insurance, road safety standards, and operational liabilities.

- **Techno-economic challenges**

The combination of elevated initial investment and specialized operational upkeep is a significant barrier. The upfront CAPEX for industrial-grade batteries, solar cells, and smart micro-controllers remains high because local supply chains rely heavily on imported electronics. Technically, managing the real-time power balance between variable solar generation and charging spikes requires sophisticated software control, while maintaining these systems in remote regions drives up OPEX due to a lack of local technical experts [12].

- **Social challenges**

Shifting long-standing transport habits remains a social challenge due to a strong cultural reliance on personal cars and fossil-fuel-driven motorcycles. Furthermore, the longevity of a shared asset model depends entirely on community care; risks of equipment vandalism or theft require the integration of security tracking systems and targeted campus awareness campaigns.

- **Environmental challenges**

The harsh Saharan climate around El Oued poses severe physical risks to equipment. Air temperatures frequently exceeding 45°C trigger heavy thermal stress, lowering PV conversion efficiency and shortening battery lifespans [12]. Additionally, frequent desert dust and sandstorms cause heavy soiling on the modules, requiring continuous cleaning to prevent catastrophic drops in daily power yield.

7.2. Opportunities for solar charging shared e-mobility systems in Algeria

Despite the existing challenges, the deployment of solar-powered shared e-mobility systems at the University of El Oued presents a transformative opportunity. By leveraging the region's natural resources and aligning with national sustainability goals, this initiative can serve as a catalyst for innovation and a benchmark for modernizing institutional transport infrastructure.

- **Political opportunities**

The project fits perfectly within the scope of Algeria's National Renewable Energy Program, which incentivizes clean technology adoption [12]. By successfully launching this infrastructure at the University of El Oued, the institution can serve as an empirical "Green Campus" testing ground, generating real-world data to help policymakers draft national micro-mobility regulations.

- **Techno-economic opportunities**

Leveraging El Oued's exceptional GHI allows the university to drastically reduce its long-term grid power expenses. Because the campus operates primarily between 8:00 AM and 5:00 PM, direct daylight charging is highly achievable, lowering the requirement for high-capacity, costly battery storage. Furthermore, localized maintenance needs to open a technical niche for regional tech startups and engineering students to gain practical experience in green tech maintenance.

- **Social opportunities**

The network directly resolves an ongoing social problem: the lack of reliable internal and external transport links across the university campus. E-scooters offer an affordable, modern, and highly flexible "last-mile" transit solution for students and staff. This infrastructure enhances overall campus life by mitigating traffic noise and exhaust congestion, while building a tech-forward student culture centered on shared infrastructure.

- **Environmental opportunities**

The environmental conditions across Algeria are exceptionally favorable for the deployment of solar-powered infrastructure due to the country's superior solar resource potential. Algeria possesses one of the highest global horizontal irradiances (GHI) levels in the world, particularly in its southern and desert regions, providing a consistent and powerful energy supply that ensures solar charging stations can operate at high efficiency [14]. This vast solar abundance makes the Algerian environment an ideal setting for integrating renewable energy with e-mobility. Furthermore, the project is inherently eco-friendly, as it provides a clean energy alternative that significantly contributes to reducing carbon emissions and minimizing the environmental footprint of the transportation sector.

8. Conclusion

This chapter reviewed the existing literature regarding the integration of solar photovoltaic installations into electric micro-mobility charging infrastructures. The compiled research proves that transitioning to shared e-scooters offers a vital pathway for decarbonizing institutional transit, provided the underlying charging electricity is supplied by renewable sources rather than carbon-heavy regional power grids.

Historical climate data confirms that southern Algeria, particularly El Oued Province, offers an exceptional solar environment for these applications due to high daily irradiance profiles and flat urban terrains. Nevertheless, the literature highlights persistent engineering bottlenecks, including solar intermittency, heavy sand soiling, and high thermal stress in arid zones. Economically, while commercial PV prices continue to fall globally, balancing the initial CAPEX with specialized desert OPEX requires rigorous techno-economic optimization.

Crucially, this review identified a clear research gap: most existing publications address full-scale electric vehicles, leaving a shortage of optimized engineering designs for shared e-scooter networks tailored specifically to the unique climate and socioeconomic context of Algerian universities. To address this gap, this thesis develops a definitive framework for modelling an optimized solar-powered shared e-mobility network at the University of El Oued. The theoretical baselines established here lead directly to **Chapter 2 (Methodology)**, which introduces the mathematical modelling techniques used to evaluate this sector-coupled hybrid energy system combining power grids, solar PV, batteries, and dynamic e-scooter power demands.

CHAPTER 02:

Methodology

Chapter 2. Methodology

1. Introduction

This chapter presents a comprehensive methodological framework designed to evaluate and optimize the technical, economic, environmental, and social performance of a solar-powered charging infrastructure for shared electric scooters at the University of El Oued. The methodology is structured to ensure a systematic approach to system sizing and sustainability assessment, bridging the gap between theoretical modeling and practical implementation within an Algerian educational campus context [14].

To achieve these objectives, the study integrates real-world meteorological data of the El Oued region with high-resolution electric scooter load profiles tailored to student commuting patterns. Mathematical models for photovoltaic (PV) modules, battery storage systems, and power converters are employed to simulate the energy flow. Furthermore, the optimization process utilizes HOMER Pro software to identify the most cost-effective configurations focusing on key indicators such as Net Present Cost (NPC) and Levelized Cost of Energy (LCOE) [15].

Beyond the technical analysis, this methodology incorporates a social sustainability assessment, exploring the impact of shared electric mobility on campus life, student accessibility, and the promotion of a green culture. By addressing the social dimension, the study ensures that the proposed solution is not only technically feasible but also socially acceptable and beneficial to the university community.

2. Study Area and Solar Resource Assessment

The University of El Oued is situated in the southeastern region of Algeria, specifically at the coordinates 33.35° N latitude and 6.86° E longitude. This region, known as the "City of a Thousand Domes," is in the heart of the Sahara Desert. The campus provides a vast open area with minimal shading, making it an ideal environment for the deployment of decentralized solar photovoltaic (PV) systems. Choosing this location is strategic for promoting sustainable mobility solutions like electric scooters due to the flat terrain and the high concentration of student activities.

The climate of El Oued is characterized as arid, with extremely hot summers where temperatures can exceed 45°C, and mild winters. While high temperatures can slightly decrease the efficiency of PV modules (temperature derating) [16], the region benefits from very low cloud cover throughout the year.

Algeria is characterized by one of the highest solar irradiation levels worldwide, and the ElOued region is no exception. In this study, Global Horizontal Irradiance (GHI) and the clearness index were obtained from the NASA POWER database [17]. The peak solar irradiation in this region reached 8.22kWh/m²/day (July 2025), with more than 3,500 sunshine hours annually [18]. This abundant solar resource provides a strong energy basis for charging electric scooter batteries, significantly reducing dependence on the national grid and lowering the carbon footprint of mobility within the university campus. Solar Resource Mapping and Site Selection for Photovoltaic Installations at the University of Echahid Hamma Lakhdar are presented in Fig.1, and Fig.2.

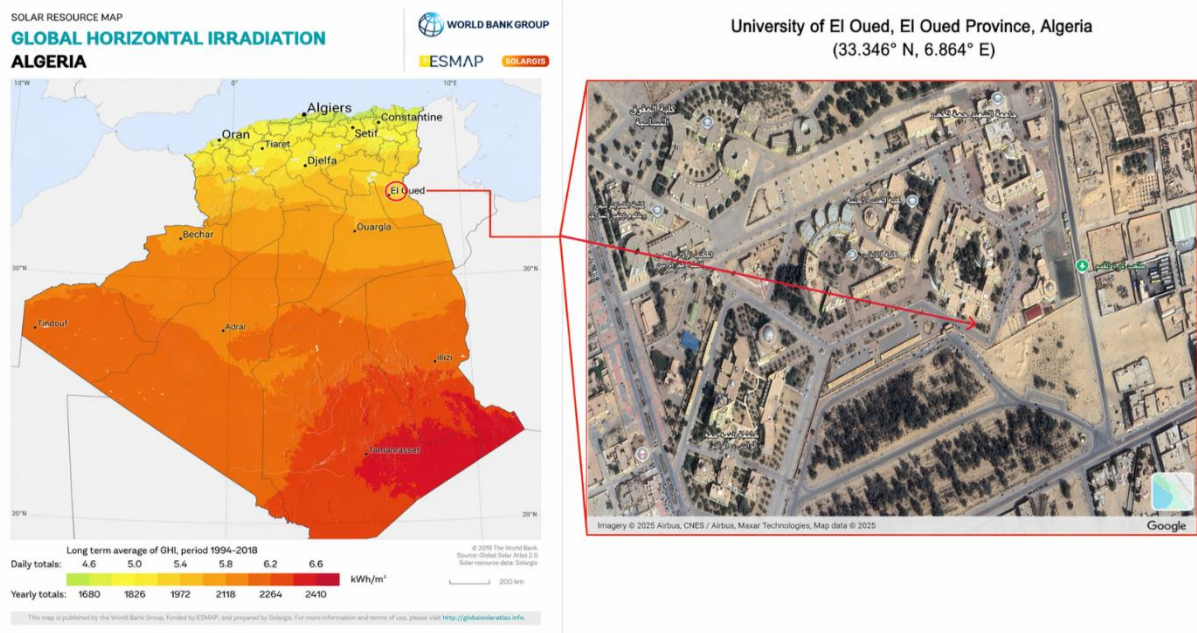


Figure 1. Solar Resource Mapping and Site Selection for Photovoltaic Installations at the University of Echahid Hamma Lakhdar

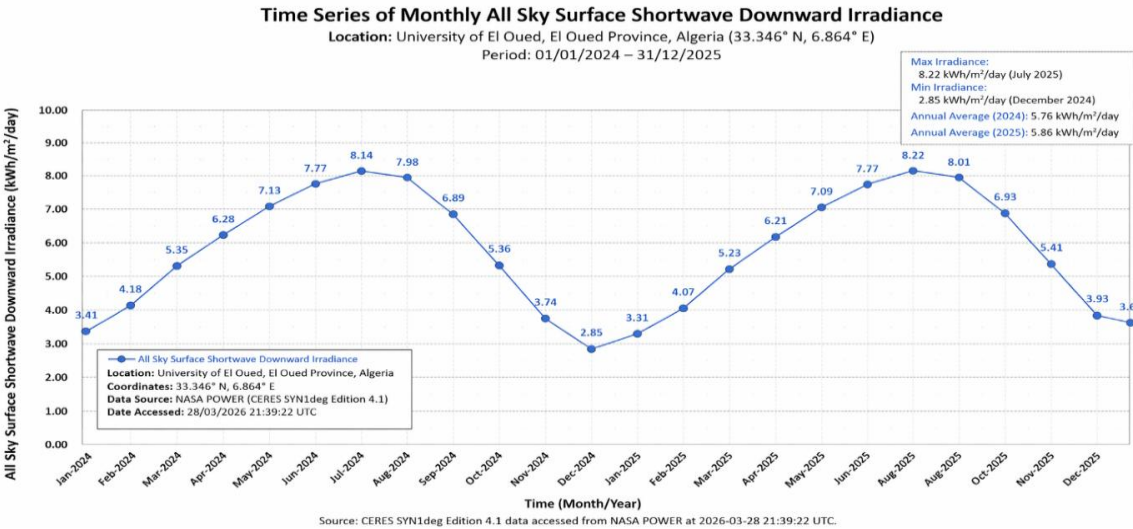


Figure 2: Time Series of Monthly Global Horizontal Irradiance (GHI) in El Oued (2025-2024)

3. System Architecture and Components Overview

3.1. Proposed System Configuration

Based on the optimization requirements for the University of El Oued, a Grid-Connected PV-Battery Hybrid Topology is adopted. This configuration is strategically chosen to balance between energy autonomy (Sustainability) and system reliability.

3.2. Functional Block Diagram (System Layout)

The system architecture presented in the schematic reflects a DC-coupled hybrid configuration, chosen specifically to enhance the overall energy efficiency of the charging station. In this topology, the core integration occurs at the Direct Current (DC) level to minimize unnecessary power conversion stages. The system is designed to manage the charging demand of a fleet consisting of several e-scooters, where the sizing of each component is optimized to meet the cumulative energy requirements.

3.2.1 The DC Bus: Renewable Integration and Load Management

The DC bus serves as the central hub for energy distribution.

- **PV Array:** Connected via an MPPT logic to harvest maximum solar power. It provides the primary energy source for charging the **(N) scooters**.
- **Storage Candidates (Li-ion & Lead-Acid):** Both battery technologies are linked to this bus. Their role is to act as an energy buffer, storing excess solar power to be used for charging the scooters when solar irradiance is insufficient or during the evening.
- **The Charging Load:** By placing the charging docks for the **(N) scooters** on the DC bus, the system eliminates the need for an AC-to-DC conversion step for each charger. This reduces thermal losses and increases the "Solar-to-Battery" efficiency [19].

3.2.2 The AC Bus and Bi-directional Power Conversion

The AC bus handles the interaction with the University's electrical grid.

- **National Grid:** Acts as a secondary backup. If the solar array and the stationary batteries cannot meet the demand of the (N) scooters, the grid provides the necessary deficit.
- **Bidirectional Converter:** This is the critical interface. It functions as an **Inverter** when there is a need to support AC campus loads with solar energy, and as a **Rectifier** when grid electricity is required to flow into the DC bus to charge the stationary storage or the scooters.

The system under study as presented in Fig.3. includes solar PV as the primary energy source, supported by a battery bank for storage and the national grid for backup:

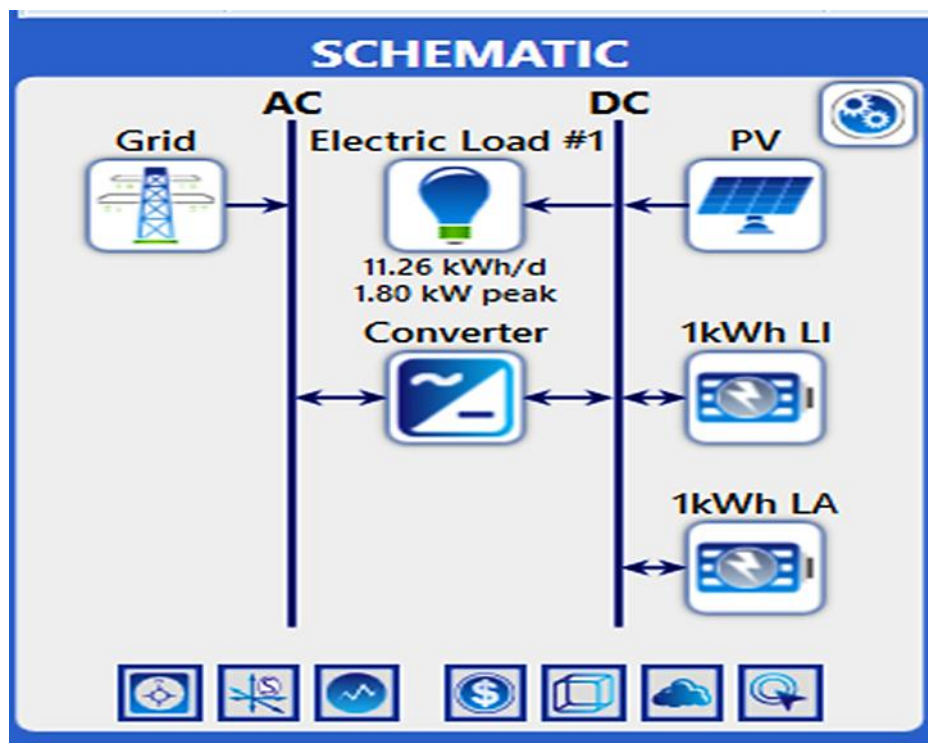


Figure 3: HOMER Pro Simulation of a Solar Charging System

4. Mathematical Modeling of System Components

This section defines the mathematical formulations used to simulate the energy behaviour of the charging station. Each component's performance is governed by specific physical and electrical equations [20].

4.1. Solar PV Modeling

Thermal Power Output Model

The power supplied by the PV array is calculated as a function of solar radiation and temperature. The model accounts for the efficiency drop in El Oued high-temperature environment using Eq. 1 [20]:

$$P_{pv} = P_{Npv} \times \frac{G}{G_{ref}} \times [1 + K_t \times ([T_{amb} + \frac{NOCT-20}{800}] \times G - T_{ref})] \quad \text{--- (1)}$$

- **Variables:**

P_{pv}, P_{Npv} : Output and rated power.

G, G_{ref} : Actual and reference irradiance ($1kW/m^2$).

T_{amb}, T_{ref} : Ambient and reference temperature ($25^\circ C$).

K_t : Temperature coefficient.

$NOCT$: Nominal Operating Cell Temperature

Single-Diode Electrical Model

For a deeper technical analysis of the electrical behaviour (Current-Voltage curve), the one-diode model is employed through Eq. 2, 3, and 4 [20]:

- **I-V Curve Relationship:**

$$I(V) = I_{ph} - I_o [e^{\left(\frac{q(V+IR_s)}{nkT N_{cs}}\right)} - 1] - \frac{V+IR_s}{R_{sh}} \quad \text{--- (2)}$$

- **Photocurrent Calculation:**

$$I_{ph} = \frac{G}{G_0} [I_{ph,STC} + \gamma(T - 298)] \quad \text{--- (3)}$$

- **Reverse Saturation Current:**

$$I_o = I_{o,STC} \left(\frac{T}{298}\right)^3 e^{\left[\left(\frac{qE_g}{nk}\right)\left(\frac{1}{298} - \frac{1}{T}\right)\right]} \quad \text{--- (4)}$$

- **Parameters Explanation:**

I, V : Current and voltage of the PV module.

I_{ph}, I_o : Photocurrent and reverse saturation current.

R_s, R_{sh} : Series and shunt resistance.

q, k, n : Electron charge, Boltzmann constant, and diode ideality factor.

γ : Temperature coefficient of short-circuit current.

4.2. Battery Storage Model (State of Charge)

The State of Charge (SoC) represents the cumulative energy balance. It is derived from the law of conservation of energy [20]:

- **Energy Flow:** The change in stored energy (ΔE) over a time step (Δt) is the difference between charging power and discharging power:

$$\Delta E = (P_{PV} - P_{Load}) \cdot \Delta t \quad \text{--- (5)}$$

- **Efficiency and Losses:** We must include charging efficiency (η_{ch}) and the self-discharge rate (σ):

$$E(t) = E(t - 1) \cdot (1 - \sigma) + (P_{bat} \cdot \Delta t \cdot \eta_{bat}) \quad \text{--- (6)}$$

Normalization: To convert energy into a percentage (SoC), we divide by the rated capacity (E_{rated}):

$$SoC(t) = SoC(t - 1) \cdot (1 - \sigma) + \left(\frac{P_{bat} \cdot \Delta t \cdot \eta_{bat}}{E_{rated}} \right) \quad \text{--- (7)}$$

$SoC(t)$: State of Charge at the current time step (%).

$SoC(t - 1)$: State of Charge at the previous time step (%)

σ : Self-discharge rate of the battery.

$P_{bat}(t)$: Charge or discharge power (W).

Δt : Duration of the time step (typically 1 hour).

η_{bat} : Round-trip efficiency of the battery

E_{rated} : Total rated energy capacity of the battery bank (kWh).

4.3. DC-DC Converter Model

For the scooter charging process, a DC-DC converter regulates the voltage. The derivation is based on the power balance:

- **Power Conservation:** In an ideal world, $P_{in} = P_{out}$. Internal losses (heat) occur:

$$P_{out} = P_{in} - P_{losses} \quad \text{--- (8)}$$

- **Efficiency Definition:** Efficiency (η) is the ratio of output power to input power:

$$\eta_{DC/DC} = \frac{P_{out}}{P_{in}} \quad \text{--- (9)}$$

- **Final Formulation:** The power delivered to the scooters is:

$$P_{Scooters} = P_{Bus_DC} \cdot \eta_{DC} \quad \text{--- (10)}$$

4.4. Bidirectional DC/AC Converter Model

This converter is essential for connecting the photovoltaic panels and battery system (DC) to the university grid or any loads operating on alternating current (AC) [19].

- **Energy Conversion Principle:** The primary function is to convert DC power (P_{DC}) into AC power (P_{AC}). The fundamental efficiency relationship is:

$$\eta_{inv} = \frac{P_{AC}}{P_{DC}} \quad \text{--- (11)}$$

- **Power Loss Modelling:** In real-world applications, power is lost due to switching and conduction within the electronic components (IGBTs/MOSFETs):

$$P_{AC} = P_{DC} - P_{loss} \quad \text{--- (12)}$$

- **Efficiency Variation:** The inverter efficiency is not constant; it depends on the load ratio ($\chi = P_{AC}/P_{rated}$). However, for system-level modeling, an average efficiency is used.
- **Final Formulation:** The total power available to the AC load or grid is:

$$P_{AC}(t) = P_{DC,in}(t) \cdot \eta_{inv} \quad \text{--- (13)}$$

P_{AC} : Output power from the converter (W).

$P_{DC,in}$: Input power to the converter (W).

η_{inv} : Efficiency of the power converter.

4.5. Scooter Charging Demand Model

This derivation shows how we convert the “scooter demand” into an “electrical load” on the station.

- **Individual Energy Need:** Each scooter (i) requires energy to move its State of Charge (SoC) from an initial level (SoC_{init}) to a target level (SoC_{target}):

$$E_{unit,i} = C_{batt} \cdot (SoC_{target} - SoC_{init,i}) \quad \text{--- (14)}$$

- **Total Fleet Demand:** For a fleet of N scooters, the total net energy required is the sum of individual needs:

$$E_{net} = \sum_{i=1}^N E_{unit,i} \quad \text{--- (15)}$$

- **Charger Efficiency Integration:** The energy drawn from the charging station (E_{Load}) must account for the losses in the DC-DC charger (η_{ch}):

$$E_{Load} = \frac{E_{net}}{\eta_{ch}} \quad \text{--- (16)}$$

- **Power-Time Relationship:** To find the instantaneous power demand (P_{Load}) over the charging duration (T_{ch}):

$$P_{Load} = \frac{\sum_{i=1}^N [C_{batt,i} \cdot (SoC_{target} - SoC_{init,i})]}{T_{ch} \cdot \eta_{ch}} \quad \text{--- (17)}$$

P_{Load} : Total daily energy demand for N scooters (kWh).

$C_{batt,i}$: Battery capacity of an individual scooter (kWh).

SoC_{target} : Target state of charge (usually 100%).

$SoC_{init,i}$: Initial state of charge when the scooter is plugged in.

η_{ch} : Efficiency of the scooter's onboard/external charger.

5. Operational Logic and Energy Management Strategy (EMS)

To ensure the optimal operation of any energy system, a control system should be applied which follows a defined Energy Management Strategy (EMS). Fig.4 illustrates the proposed Energy Management Strategy (EMS) for the solar-powered charging station at the University of El Oued. The algorithm follows a hierarchical control logic designed to prioritize renewable energy penetration, ensure charging reliability for the electric scooters, and extend the lifespan of the battery storage system. The process is executed in discrete time steps, starting with the monitoring of three critical inputs: the instantaneous photovoltaic power (P_pV), the cumulative scooter charging demand (P_{Load}), and the battery's State of Charge (SoC).

The Surplus Path:

When solar production exceeds the charging demand ($P_{PV} \geq P_{Load}$), the system operates in "Surplus Mode". The PV array directly supplies power to the scooters to minimize conversion losses. Simultaneously, the logic checks the battery status; if the battery is not full, the excess solar energy is diverted to charge the battery bank. Once the batteries reach their maximum capacity.

The Deficit Path:

In the event of insufficient solar radiation ($P_{PV} < P_{Load}$), the system enters "Deficit Mode". The available PV power is utilized partially, and the gap is bridged by the storage system. However, to protect the batteries from deep discharge, the algorithm evaluates the condition ($SoC > SoC_{min}$). If the battery level is within safe limits, it discharges to cover the energy deficit. If the battery reaches its minimum safety threshold (SoC_{min}), the system seamlessly switches to the University Grid to ensure the charging process is never interrupted. This strategy minimizes grid dependency while maintaining 100% reliability for the shared mobility fleet [19].

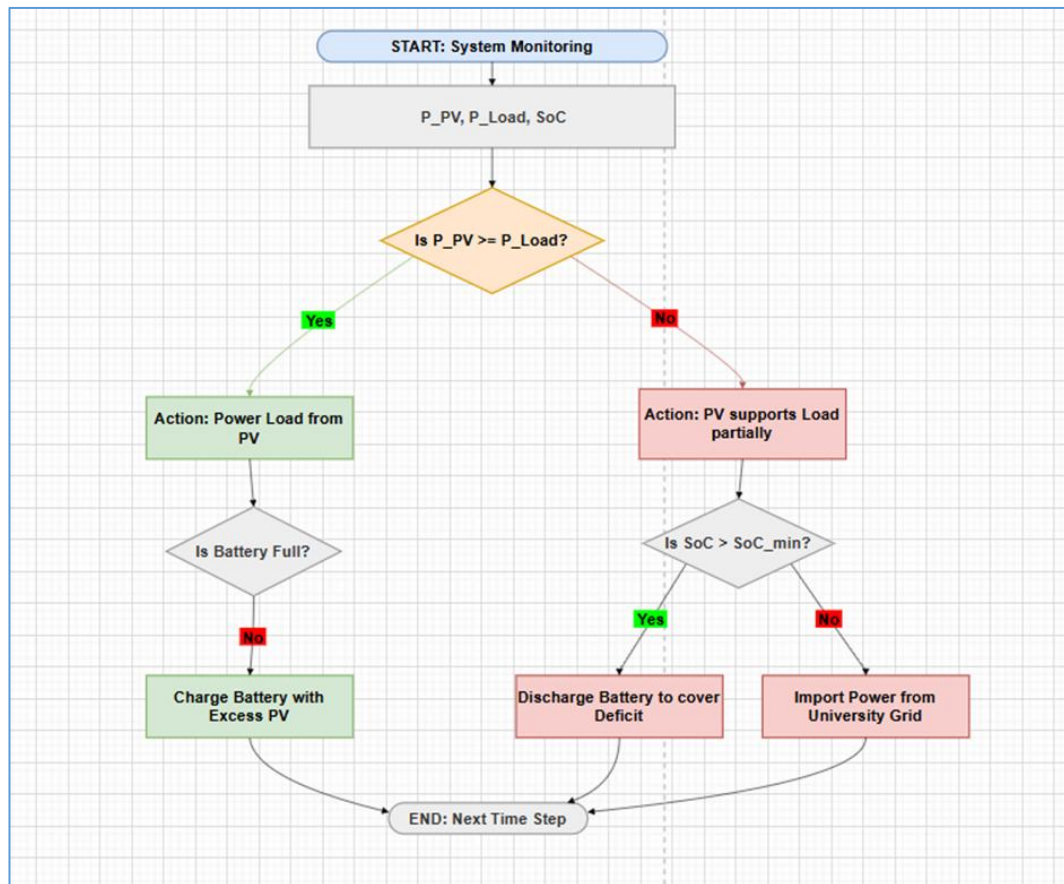


Figure 4: Flowchart of the Energy Management Strategy (EMS) for the Solar-Powered Scooter Charging Station.

6. Definition of Operational Charging Scenarios (Protocols)

The core of the optimization process lies in identifying the most efficient charging protocol. To achieve this, the methodology establishes three distinct operational scenarios. These scenarios represent different student behaviours and energy management strategies, which will be simulated and compared in the results phase:

- **Protocol 1: Conventional Evening Charging (Baseline)**

All scooters are used throughout the day and returned to the station at 17:00 for simultaneous charging.

Technical Goal: To evaluate the maximum stress on the stationary battery during non-solar hours.

- **Protocol 2: Uncontrolled Daytime Charging**

Charging occurs whenever a scooter is plugged in, regardless of the solar peak.

Technical Goal: To monitor the fluctuation of solar energy utilization based on random student arrivals.

- **Protocol 3: Proposed "Split-Fleet" Rotation Protocol (50/50 Strategy)**

The fleet is divided such that 50% of the scooters are charged during peak solar hours, while the other 50% are in use, followed by a rotation or evening charging process.

Technical Goal: To test the hypothesis that direct solar-to-scooter charging significantly reduces energy losses and battery size.

7. Simulation and Optimization Tool: HOMER Pro

HOMER Pro (Hybrid Optimization Model for Multiple Energy Resources) is a powerful and globally recognized software tool designed for the planning and optimization of Hybrid Energy Systems (HES). In this study, it is utilized to determine the optimal configuration and sizing of the solar charging station components at the University of El Oued. The software operates through three main analytical stages [15]:

- **Simulation:** Modelling the hourly energy flow between solar resources, battery storage, and the 20-scooter load.
- **Optimization:** Finding the best system architecture that satisfies the charging demand at the lowest cost.
- **Sensitivity Analysis:** Testing how changes in variables (like PV costs or grid prices) affect the system's viability.

7.1. Model Input and Output Parameters

The software evaluates various system configurations and ranks them based on the Net Present Cost (NPC) and the Levelized Cost of Energy (LCOE). For the specific case of the electric scooter charging station in El Oued, the following parameters are integrated into the model:

7.1.1. Model Inputs

- **Solar Resource Data:** Site-specific climate data for El Oued (Irradiance and Temperature) [17].
- **Capital Cost of PV:** Estimated between \$700 - \$1,200/kW depending on the Algerian market [14].
- **Operation and Maintenance (O&M):** \$10 - \$20/kW/year for cleaning and technical check-ups.
- **Project Lifetime:** Set at 20 - 25 years.
- **Discount Rate:** 6% - 10% to account for the time value of money in Algeria.
- **Scooter Load Profiles:** The three proposed charging protocols defined in Section 6.
- **Grid Connection (Utility Interface):** The national grid (Sonelgaz) is integrated as a secondary power source to ensure 100% charging reliability, especially during consecutive cloudy days or for the nightshift charging protocol. the price is estimated at 0.04 - 0.05 \$/kWh [14].

7.1.2. Model Outputs

- **Net Present Cost (NPC):** Total life-cycle cost in USD.
- **Levelized Cost of Energy (LCOE):** Cost per kWh of electricity produced (USD/kWh).
- **Annual Energy Savings:** Total energy shifted from the grid to solar power.
- **Environmental Impact:** Annual reduction in CO₂ emissions (kg CO₂/year).

7.2. Sensitivity analysis

Selecting system components such as the appropriate solar PV modules and storage technology is vital for system longevity and performance. This study does not assume a single battery type; instead, it proposes a comparative methodology between two distinct technologies. The mathematical and technical characteristics of both candidates are modelled as follows:

- **Candidate A: Lead-Acid (Sodium/Acid) Technology:** Representing the conventional, low-cost solution. The study models its behaviour focusing on its lower depth of discharge (DoD) and its sensitivity to high Saharan temperatures.
- **Candidate B: Lithium-ion Technology:** Representing the modern, high-performance solution. The model incorporates its high energy density and superior cycle life to evaluate if its higher initial cost is justified by its long-term performance in El Oued.

8. Sustainability assessment of the solar charging shared mobility system

8.1. Techno-Economic Evaluation Criteria

This section defines the financial metrics used to determine the feasibility of the solar charging station.

Net Present Cost (NPC): is the most critical economic indicator in the sustainability assessment. It represents the "Present Value" of all costs incurred over the project's lifetime (25 years), minus the present value of all revenue earned.

- **Why NPC?** It follows the **Time Value of Money** principle. A project in El Oued requires high initial capital for Lithium batteries. However, Lead-acid batteries might look cheaper now but require frequent replacement every 3 years. NPC discounts these future replacement costs back to today's value, allowing for a fair comparison.

- **Components of NPC**

Capital Costs (C_{cap}): The price of panels, batteries, and converters today.

Operating & Maintenance ($C_{O\&M}$): Annual costs like cleaning dust off panels in El Oued.

Replacement Costs (C_{rep}): Future costs to replace batteries or inverters.

Salvage Value (S): The estimated resale value of components at the end of year 25.

- **Formula**

$$NPC = \frac{C_{ann,tot}}{CRF(i,R_{proj})}, \text{ where } CRF \text{ is the Capital Recovery Factor.}$$

Levelized Cost of Energy (LCOE): is the average cost per kilowatt-hour (kWh) of useful electricity produced by the system.

- **Significance:** It serves as the "Break-even" price. If the LCOE of our solar station is $0.03/kWh$ and the University grid price is $0.05/kWh$, the solar system is economically superior.
- **Economic Rationale:** LCOE combines both the fixed (Capital) and variable (O&M) costs into a single unit price [2]. This is crucial for the University of El Oued to justify the transition from grid dependency to solar independence.
- **Formula:** $LCOE = \frac{C_{ann,tot}}{E_{served_AC} + E_{served_DC}}$. It is the total annualized cost divided by the total energy delivered to the scooters.

8.2. Environmental Sustainability Assessment

The environmental impact is evaluated by measuring the reduction in greenhouse gas emissions. Sustainability is measured by how much "dirty" grid energy is replaced by "clean" solar energy for the scooters.

CO2 Savings Calculation: The annual avoided emissions are calculated by multiplying the solar energy consumed by the emission factor of the Algerian national grid (approx. $0.6 \text{ kg CO}_2/kWh$).

8.3. Social Sustainability Assessment

The social dimension is a fundamental pillar of sustainability in this study. The implementation of a solar-powered shared scooter system at the University of El Oued is evaluated based on its impact on the campus community and student quality of life. The social assessment focuses on three key areas evaluated mainly through a survey and interviews with sample students, faculties and administrators belonging to the campus.

- **Enhanced Student Mobility**

Measuring the reduction in travel time between distant faculties and laboratories, especially under the extreme heat conditions of El Oued.

- **Affordability and Equity**

Evaluating the provision of a low-cost, clean transportation alternative for students who do not own private vehicles, ensuring equal access to campus facilities.

- **Promoting Green Campus Culture**

Assessing the role of the project in raising environmental awareness among students and staff, encouraging a transition towards sustainable "Smart Cities" initiatives in Algeria.

- **The Administrative and Operational Dimension**

Institutional Efficiency: Evaluating the university's capacity to manage the fleet, maintenance protocols, and charging schedules as part of its "Smart Campus" strategy.

Branding and Image: Assessing how the project enhances the University of El Oued reputation as a pioneer in green innovation among Algerian universities.

- **The Political and Strategic Dimension**

National Energy Transition: Aligning the project with Algeria's 2030 Renewable Energy Program and the national commitments to the Paris Agreement (CO2 reduction) [4].

Political Will: Analysing the role of state-driven initiatives in supporting local sustainable mobility as a model for decentralized energy solutions.

9. Conclusion

In conclusion, this chapter has established a comprehensive methodological framework covering the technical, economic, environmental, and social dimensions of the solar charging station. By defining these criteria and using HOMER Pro for optimization, three different scenarios were developed. The simulation results, along with a detailed performance analysis, will be presented and discussed in the final chapter: Results and Discussion.

CHAPTER 03: Case study simulation, results and discussions

1. Introduction

This chapter constitutes the analytical phase of the research, transitioning from the theoretical modelling in Chapter 2 to the quantitative evaluation of the proposed infrastructure. The primary objective is to analyse the performance and sustainability of a solar-powered charging station optimized for a fleet of 20 shared electric scooters at the University of El Oued. the electrification of micro-mobility through solar energy is a critical step in reducing the transport sector's contribution to global energy consumption and greenhouse gas emissions. By focusing on a 20-unit fleet, this study provides a scalable and realistic model for Algerian educational campuses, aligning with the national energy transition strategy and the "Green Campus" initiative [10].

To achieve robust results, the simulation was executed using HOMER Pro software, integrating real-world meteorological data from El Oued, where solar irradiance levels are among the highest globally, often exceeding $6.5 \text{ kWh/m}^2/\text{day}$ [18]. The analysis evaluates the energy dynamics of the 20-scooter load under the four operational protocols defined in the methodology, focusing on the synergy between PV generation and battery storage. the study examines how the "One-Diode Model" and optimized charging schedules can overcome the technical challenges of intermittent solar energy and high Saharan temperatures.

Furthermore, the sustainability assessment in this chapter is multi-dimensional, covering technical, economic, environmental, and social aspects. A key highlight is the integration of field survey results to evaluate student acceptance and the potential impact of the 20-scooter system on campus productivity. this chapter provides a detailed breakdown of the Net Present Cost (NPC) and Levelized Cost of Energy (LCOE), ensuring that the proposed solution is not only technologically advanced but also economically viable and socially inclusive for the University of Echahid Hamma Lakhdar.

2. HOMER Pro Optimization Environment and System Layout

To perform a rigorous sustainability and optimization assessment, this study utilizes **HOMER Pro** as the primary simulation engine. The software is designed to execute a high-resolution, hourly simulation of energy flows over a 25-year project lifetime. For the specific case of the University of El Oued, the software integrates technical, economic, and environmental variables into a single computational framework. This allows for a precise determination of the optimal sizes for the PV array, battery storage systems (comparing Lithium-ion and Lead-Acid), and power converters to satisfy the energy demand of the **20 electric scooters**.

2.1. Technical Analysis of the System Schematic

The proposed hybrid energy system is modelled as a DC-Coupled architecture. This topology is strategically chosen to connect the PV array, both battery candidates (LI and LA), and the electric scooter load directly to the Direct Current (DC) bus. This setup minimizes energy losses by avoiding unnecessary AC-to-DC conversion stages during the primary solar charging hours. The central bidirectional converter facilitates the energy exchange with the AC university grid, ensuring that the 11.26 kWh/day load demand is consistently met, regardless of solar intermittency. Integrated System Schematic and Load Profile Interface in HOMER Pro are presented in Fig.5.



Figure 5: Integrated System Schematic and Load Profile Interface in HOMER Pro

3. Case Study Site Resources and Load Analysis

The technical performance of the solar charging infrastructure is intrinsically linked to the geographical and climatic characteristics of the University of Echahid Hamma Lakhdar in El Oued. This section provides a detailed analysis of the available energy resources and the energy demand behavior of the 20-scooter fleet, which form the baseline for the optimization process.

3.1. Meteorological Analysis of El Oued Region

The University of El Oued (33.35° N, 6.86° E) is situated in a high-radiation Saharan zone. Previous mappings of solar resources indicate that the southeastern regions of Algeria possess world-class solar potential [18]. Meteorological data retrieved for this specific site indicates an average annual Global Horizontal Irradiance (GHI) of 5.86 kWh/m²/day. As illustrated in the monthly irradiance profiles, the peak solar radiation occurs in July, reaching 8.22 kWh/m²/day, while the minimum is recorded in December at 2.85 kWh/m²/day [17] (As shown in Fig.6). However, the high ambient temperatures in the region, which frequently exceed 45°C during the summer months, trigger a "temperature derating" effect on the photovoltaic modules. This phenomenon necessitates the use of high-efficiency components to maintain system stability, as extreme heat can reduce the conversion efficiency by over 10-15% compared to standard test conditions [16].

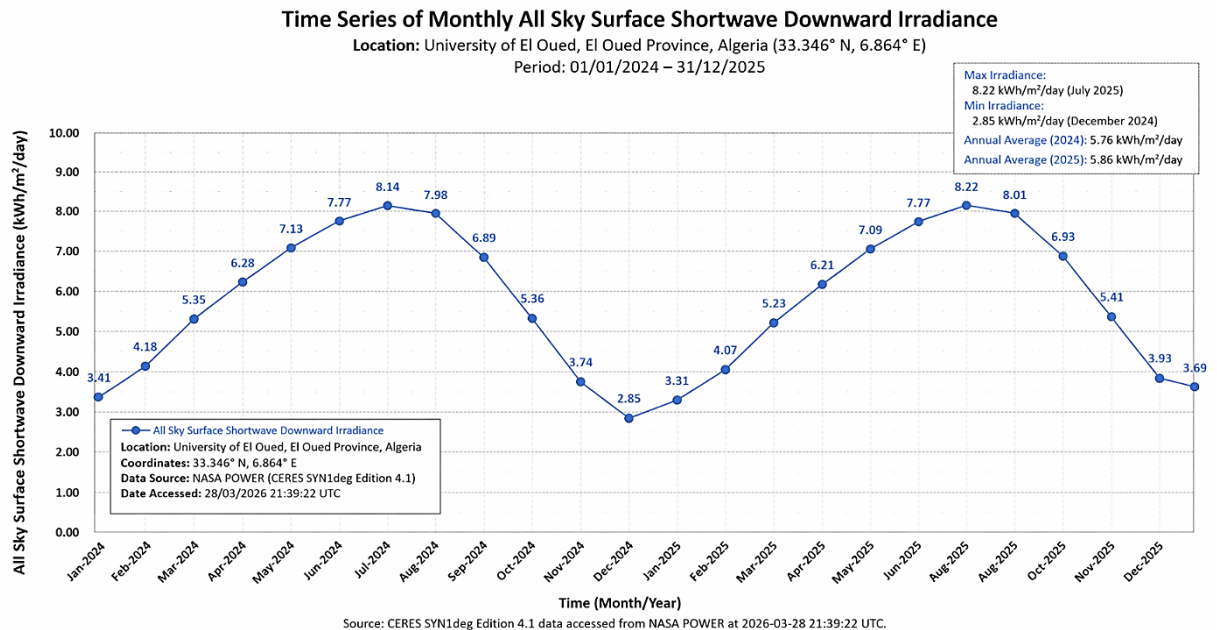


Figure 6: Time series of monthly global horizontal irradiance (GHI) in El Oued (2024–2025)

3.2. Technical Characterization and Load Calculation of the Scooter Fleet

To ensure high fidelity in the simulation, the **Xiaomi Electric Scooter 3 Pro** was selected as the reference mobility unit (As shown in Fig.7) This model is widely used in urban and campus environments and is technically compatible with the climate of El Oued. The following table and derivation detail the technical inputs and the mathematical methodology used to establish the daily energy demand for the 20-scooter fleet.

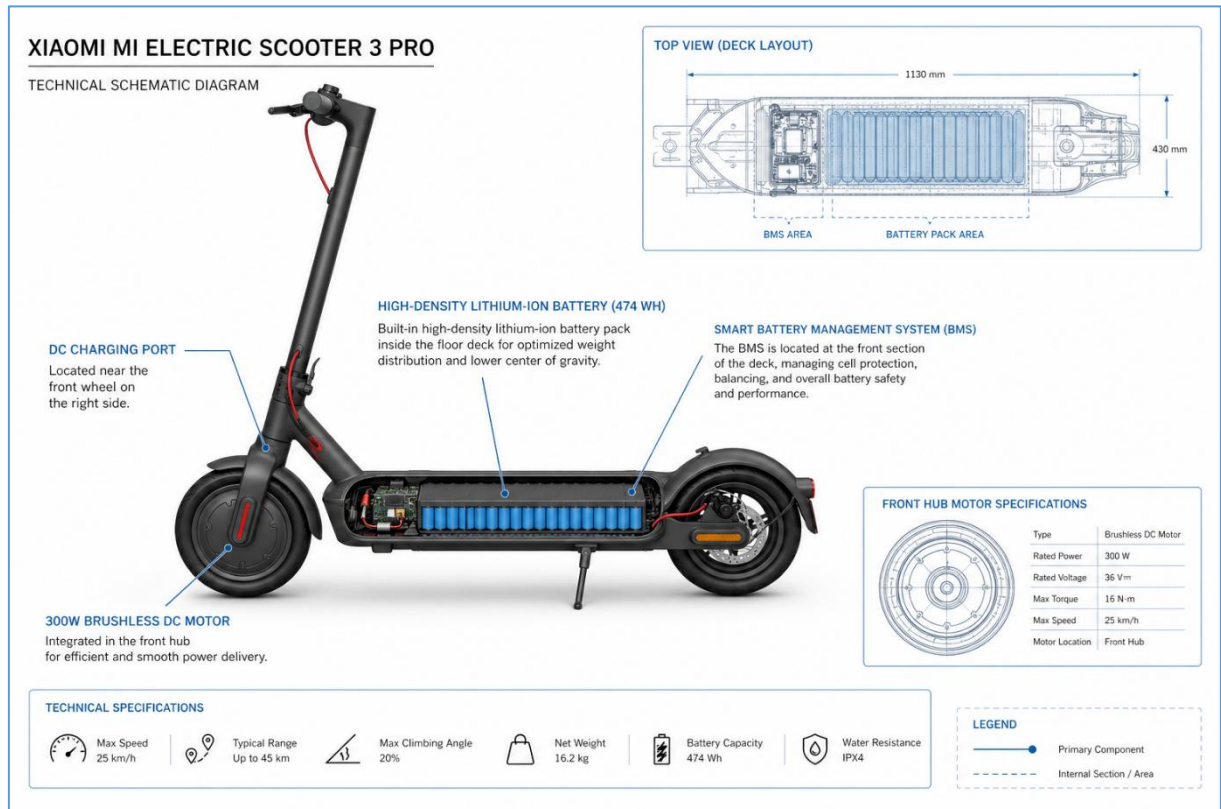


Figure 7: Technical architecture and internal components of the Xiaomi Mi 3 Pro

3.2.1. Unit Technical and Economic Data

- 5 **Battery Capacity (C_{batt}):** 474Wh.
- 6 **Charging Power (P_{ch}):** 71 W (Standard Adapter).
- 7 **Charging Time (T_{ch}):** ~8.5 hours.
- 8 **Capital Cost per Unit:** \$550.

3.2.2. Detailed Energy Load Derivation

The total daily energy requirement (E_{Total}) is calculated using a bottom-up approach, starting from a single trip and scaling up to the entire fleet of 20 units.

- **Step 1: Energy per trip (E_{trip}):**

If a student travels an average distance of 15 km per day within the campus, with an energy consumption rate of 12.5Wh per km:

$$E_{trip} = 15km \times 12.5Wh/km = 187.5Wh$$

- **Step 2: Net Fleet Demand (E_{net}):**

$$E_{net} = 20units \times 187.5Wh = 3,750Wh = 3.75kWh$$

- **Step 3: Gross Demand with System Losses (E_{Total}):**

To ensure realism, the net value must be divided by the charger efficiency ($\eta_{ch} = 0.85$) and the thermal degradation factor due to El Oued high temperature ($f_{temp} = 0.90$) [16]:

$$E_{Total} = \frac{E_{net}}{\eta_{ch} \times f_{temp}} = \frac{3.75}{0.85 \times 0.90} \approx 4.9 \frac{kWh}{day}$$

3.2.3. Discussion of Load Scaling

While the standard daily demand is calculated at 4.9 kWh/day, this study accounts for "High-Intensity Days" during exam periods or university events where usage frequency doubles. In such cases, the demand can scale up to 10-12 kWh/day. Defining this baseline is crucial because it allows the optimization software to test the system's reliability under different charging protocols without assuming a fixed schedule at this stage.

4. Results and Analysis of Protocols

4.1. Results and Analysis of Protocol 1: Full Evening Charging

This section presents the detailed simulation results for Protocol 1, which represents the "Full Evening Charging" operational behaviour. In this scenario, it is assumed that the entire fleet of 20

Xiaomi electric scooters is utilized by students throughout the campus day and returned to the station at 17:00 for simultaneous charging. Technically, this protocol is designed to evaluate the system's performance under maximum power stress, as the charging peak occurs precisely when solar irradiance begins to decline. This creates a "Temporal Mismatch" where the energy required for charging must be supplied either by discharging the stationary battery bank—harvested during the daylight hours—or by purchasing electricity directly from the national grid. This case serves as a baseline to analyse the economic and environmental costs of evening-heavy load patterns in the specific climate of El Oued.

4.1.1. Analysis of the Optimization Results Table (Protocol 1)

The optimization table (See Fig.8) ranks the three cases based on their economic and technical viability. Case 1 represents the least expensive but grid-dependent solution, while Cases 2 and 3 achieve total energy independence through the "Generator Order" (GO) dispatch strategy. Each system integrates the \$11,000 capital cost for the scooter fleet.

Optimization Results															Categorized	
Left Double Click on a particular system to see its detailed Simulation Results.																
Architecture							Cost				System		1kWh LI	1kWh LA	Grid	
   	PV (kW)	1kWh LI	1kWh LA	Converter (kW)	Dispatch	NPC (\$)	COE (\$)	Operating cost (\$/yr)	Initial capital (\$)	Ren Frac (%)	CO ₂ (kg/yr)	Nominal Capacity (kWh)	Nominal Capacity (kWh)	Energy Purchased (kWh)	Energy Sold (kWh)	
   	2.69			2.29	CC	\$16,187	\$0.156	\$243.96	\$13,033	50.4	2,512			3,975	3,916	
   	12.0	19			GO	\$27,443	\$0.522	\$366.86	\$22,700	100	0	19.0		0	0	
   	15.5		30		GO	\$33,790	\$0.642	\$932.54	\$21,734	100	0		30.0	0	0	

Figure 8: Final optimization results for the three studied cases in Protocol 1

- **Case 1: Grid-Direct PV System (No Battery):**

Technically, this system uses a 2.69 kW PV array. The electrical data shows a total production of 8,424 kWh/yr, with 47.2% (3,975 kWh/yr) being purchased from the grid because the 17:00 charging peak lacks solar irradiance. Economically, it has the lowest NPC of \$16,187 and an LCOE of \$0.156/kWh. However, its environmental impact is high, emitting 2,512 kg of CO₂ per year, as the Renewable Fraction (RF) stays at 50.4%. Detailed electrical production and consumption for the battery-less configuration are presented in Fig.9.

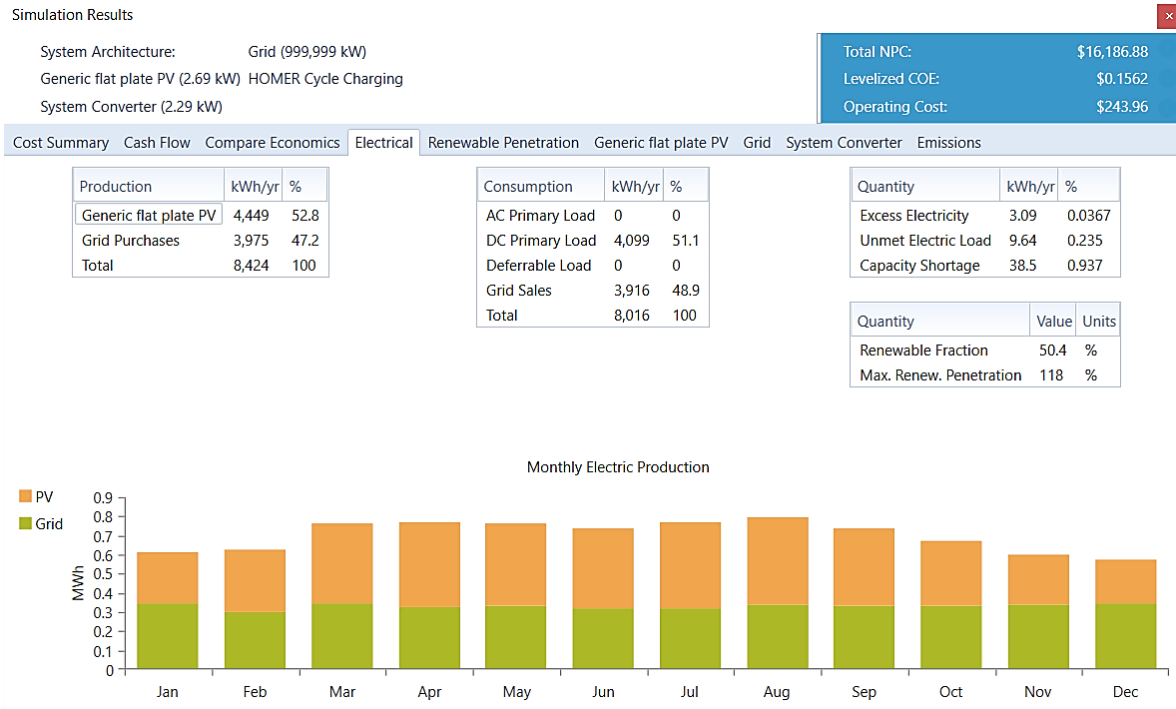


Figure 9: Detailed electrical production and consumption for the battery-less configuration

- **Case 2: 100% Autonomous Lithium-Ion System (19 kWh Storage):**

By forcing the dispatch strategy, the system uses a 12.0 kW PV array and 19 units of 1kWh Li-ion batteries. This configuration achieves a 100% Renewable Fraction with zero CO₂ emissions. Technically, the system produces 21,244 kWh/yr, resulting in a high amount of Excess Electricity (15,426 kWh/yr) to ensure reliability during winter. Economically, the NPC rises to \$27,443 with an LCOE of \$0.522/kWh, proving that total sustainability for an evening load requires a significant investment in storage. Electrical performance of the fully autonomous 19kWh Lithium-ion system are presented in Fig.10.

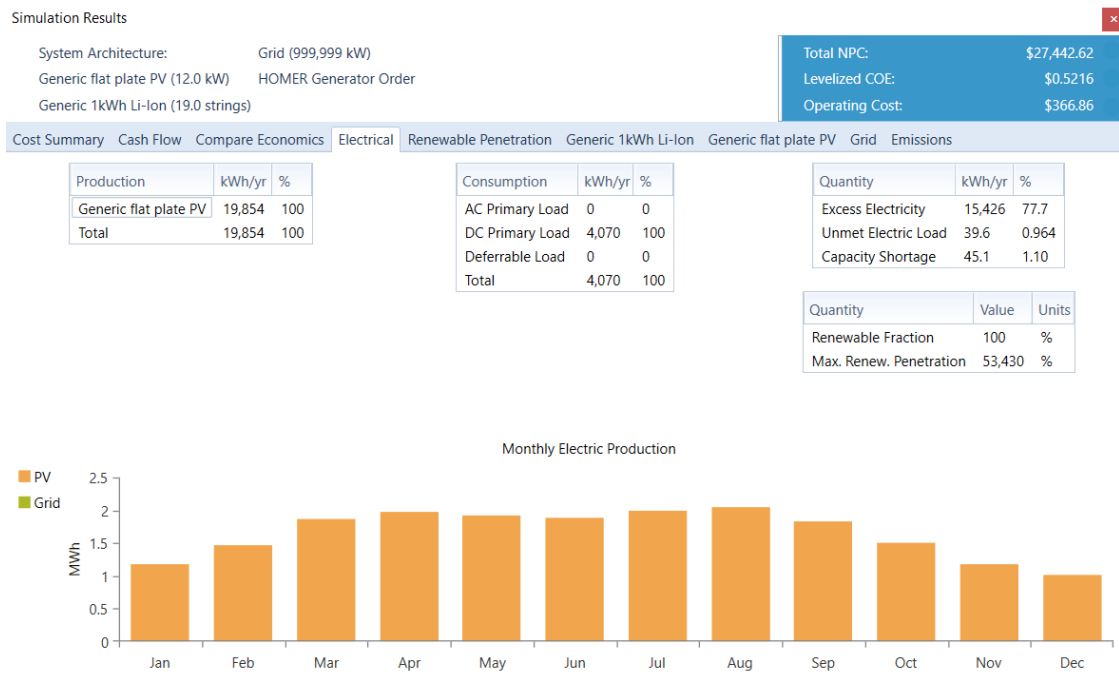


Figure 10: Electrical performance of the fully autonomous 19kWh Lithium-ion system

- **Case 3: 100% Autonomous Lead-Acid System (30 kWh Storage):**

This case uses 15.5 kW of PV and a massive 30 kWh Lead-Acid battery bank to overcome the 50% Depth of Discharge (DoD) limit. While it achieves 100% RF, it is technically less efficient than Lithium, requiring more solar panels and more storage units. Economically, it is the most expensive option with an NPC of \$33,790 and an LCOE of \$0.642/kWh. The Excess Electricity peaks at 20,711 kWh/yr, confirming the lower charge acceptance efficiency of Lead-Acid technology compared to Li-ion. Electrical metrics for the 30kWh Lead-Acid system under total autonomy are presented in Fig.11.

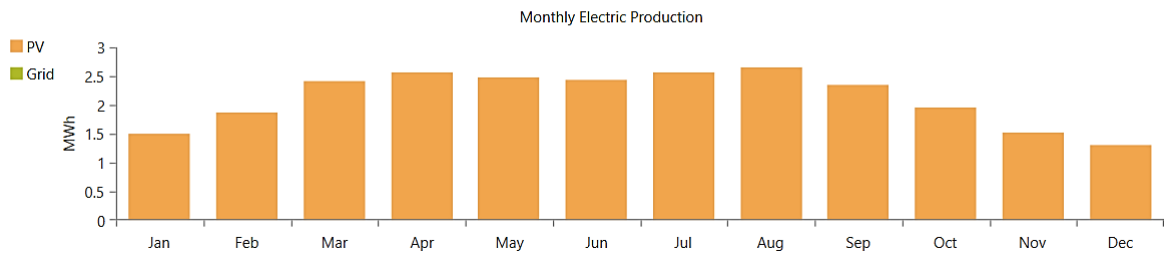
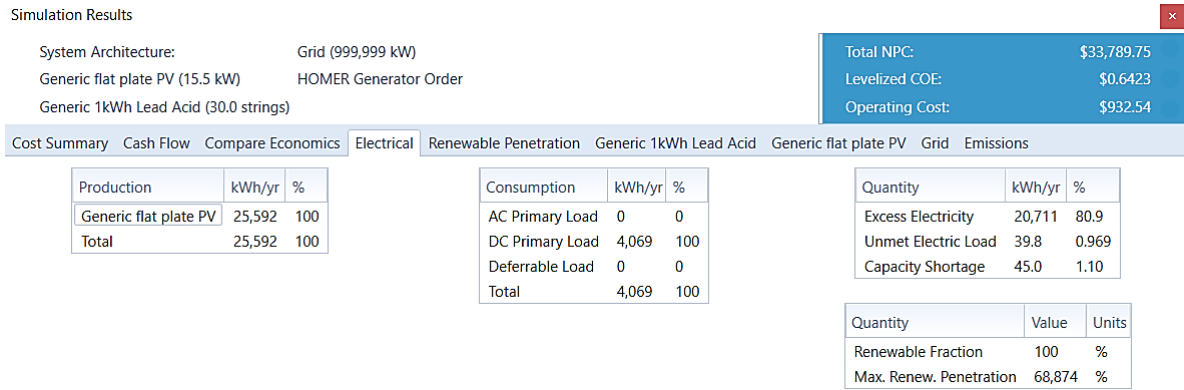


Figure 11: Electrical metrics for the 30kWh Lead-Acid system under total autonomy

4.2. Results and Analysis of Protocol 2: Uncontrolled Daytime Charging

This section investigates the simulation outcomes for Protocol 2, which models "Uncontrolled Daytime Charging" behaviour. In this scenario, it is assumed that the 20 electric scooters are plugged into the charging docks randomly throughout the university hours (08:00–16:00), matching student arrival times and lecture breaks. Technically, this protocol is designed to maximize "Solar Self-Consumption" by aligning the charging demand with the peak solar irradiance hours of the El Oued region [17]. Unlike the concentrated evening load, this strategy attempts to use the PV output directly, theoretically reducing the energy conversion losses associated with battery storage cycles. However, the stochastic (random) nature of this uncontrolled demand introduces significant power variability, testing the system's technical flexibility and its ability to maintain stability during sudden drops in solar radiation. This case provides essential insights into how "plug-and-charge" convenience for students impacts the overall Levelized Cost of Energy (LCOE) and the system's environmental footprint.

4.2.1. Analysis of the Optimization Results Table (Protocol 2)

- **Case 1: Grid-Direct PV System (No Battery):**

In this battery-less configuration, the optimizer selected a 1.84 kW PV array. The electrical analysis shows that the PV production covers 62.3% of the load (Renewable Fraction), which is

significantly higher than the 50.4% achieved in Protocol 1. This is because the load occurs during daylight, allowing for direct energy transfer. However, the system still purchases 1,767 kWh/year from the grid to cover cloudy periods and late afternoon demand. The NPC is \$13,956 and the LCOE is \$0.230/kWh, with annual emissions reduced to 1,117 kg CO₂/yr. Electrical production and consumption for the daytime battery-less configuration is presented in Fig.12.



Figure 12: Electrical metrics for the 30kWh Lead-Acid system under total autonomy

The optimization table (see Fig.13) illustrates the ranking of the three candidate systems. Case 1 (Grid-Direct) remains the most economical, while Case 2 (Lithium) and Case 3 (Lead-Acid) achieve total energy autonomy through the "Generator Order" (GO) strategy. It is observed that the required PV capacity for 100% autonomy is lower in this protocol than in the evening protocol, proving the efficiency of daytime charging.

Export...

Optimization Results

Left Double Click on a particular system to see its detailed Simulation Results.

Categorized

Architecture				Cost				System		1kWh LI	1kWh LA	Grid			
  	PV (kW)	1kWh LI	1kWh LA	Converter (kW)	Dispatch	NPC (\$)	COE (\$)	Operating cost (\$/yr)	Initial capital (\$)	Ren Frac (%)	CO ₂ (kg/yr)	Nominal Capacity (kWh)	Nominal Capacity (kWh)	Energy Purchased (kWh)	Energy Sold (kWh)
  	1.84			1.63	CC	\$13,956	\$0.230	\$119.77	\$12,407	62.3	1,117			1,767	579
  	9.10	14			GO	\$23,275	\$0.440	\$272.85	\$19,748	100	0	14.0		0	0
  	14.0		15		GO	\$26,338	\$0.498	\$528.92	\$19,500	100	0		15.0	0	0

Figure 13: Optimization results for Protocol 2 across the three studied cases

- **Case 2: Fully Autonomous Lithium-Ion System (14 kWh Storage):**

To achieve 100% RF, the system utilizes a 9.10 kW PV array and 14 kWh of Lithium-ion storage. Technically, this configuration satisfies the entire fleet demand with zero grid purchases. The "Excess Electricity" is 10,912 kWh/yr (72.5%), which is necessary to maintain reliability during low-solar winter days in El Oued. Economically, the NPC is \$23,275 and the LCOE is \$0.440/kWh. Compared to the evening protocol, Lithium storage is more efficient here as the battery is used as a buffer rather than a primary source. Electrical metrics for the 14kWh autonomous Lithium-ion daytime system are presented in Fig.14.

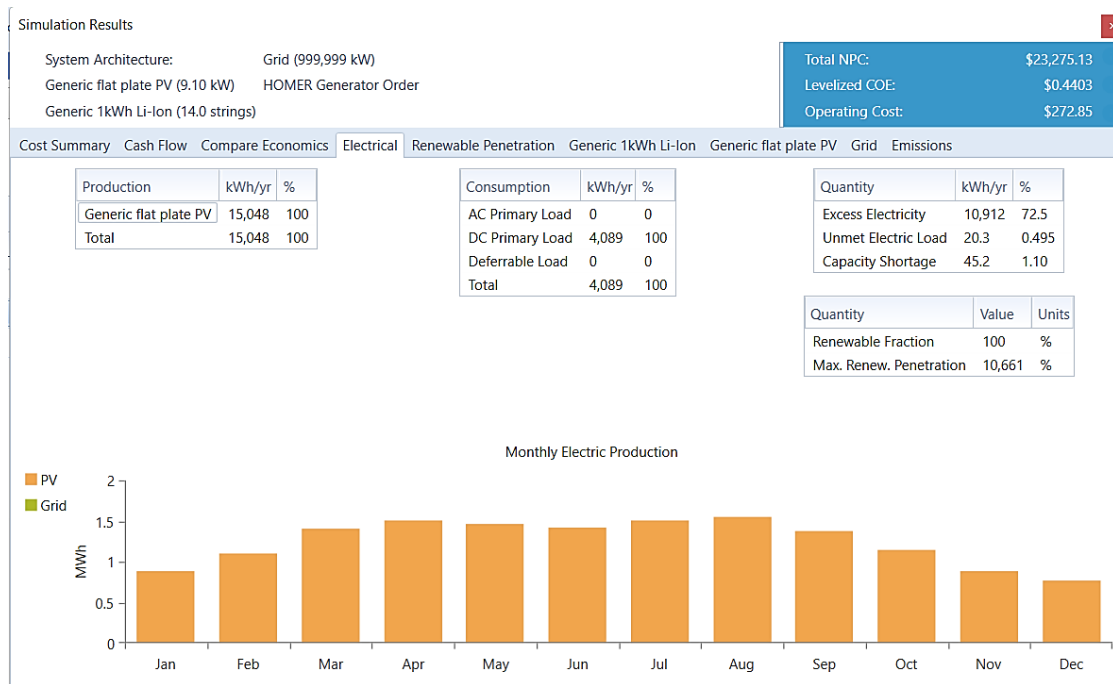


Figure 14: Electrical metrics for the 14kWh autonomous Lithium-ion daytime system

- **Case 3: Fully Autonomous Lead-Acid System (15 kWh Storage):**

The Lead-Acid configuration requires a much larger PV array of 14.0 kW to achieve 100% RF. The storage capacity is set at 15 kWh. Although it achieves total sustainability, its economic performance is lower, with the highest NPC of \$26,338 and an LCOE of \$0.498/kWh. The Excess Electricity peaks at 18,969 kWh/yr (81.9%), confirming that Lead-Acid technology's limited charge rate and 50% DoD limit force the system to over-generate power to meet the 20-scooter demand in El Oued. Electrical performance of the 15kWh Lead-Acid system for Protocol 2 are presented in Fig.15.

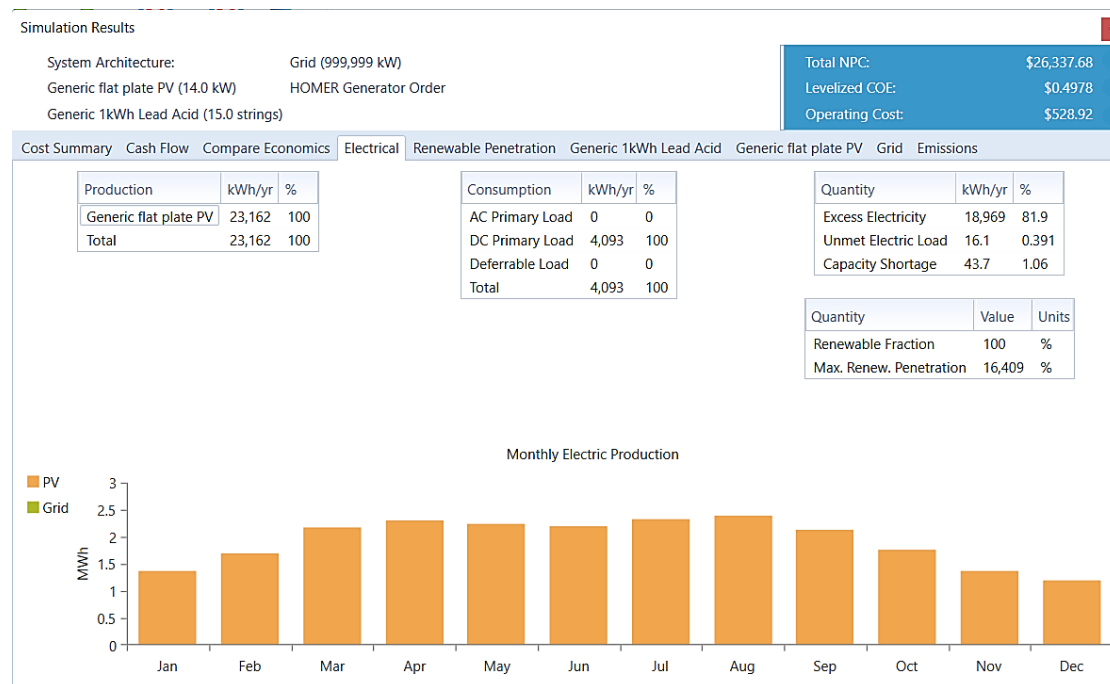


Figure 15: Electrical performance of the 15kWh Lead-Acid system for Protocol 2

4.3. Results and Analysis of Protocol 3: Optimized 50/50 Rotation Strategy

Protocol 3 represents the most advanced optimization stage in this study. It assumes a managed fleet behavior where 10 scooters are charged during peak solar hours (10:00–15:00) through direct DC-coupling, while the remaining 10 units are in active use and return for evening charging. Technically, this protocol implements "Load Shifting" and "Peak Shaving" strategies. By distributing the demand, the system aims to reduce the required size of the stationary battery bank and maximize real-time solar utilization, effectively lowering the overall cost and environmental footprint for the University of El Oued.

4.3.1. Analysis of the Optimization Results Table (Protocol 3)

Optimization results for the 50/50 rotation protocol are presented in Fig.16. The optimization results indicate a significant improvement in component sizing. Compared to the first protocol, the required storage capacity for full autonomy decreased from 19 kWh to 14 kWh for lithium batteries, and from 30 kWh to 21 kWh for lead-acid batteries. Case 1 (grid-connected direct supply) remains the most economical option, with an NPC of \$14,103, while the standalone lithium system (Case 2) offers a balanced NPC of \$24,120 with an LCOE of \$0.458/kWh. This

reduction in component sizes confirms that managing charging timing is more effective than simply increasing battery capacity.

Optimization Results														
Left Double Click on a particular system to see its detailed Simulation Results.														
Architecture					Cost				System		1kWh LI	1kWh LA	Grid	
PV (kW)	1kWh LI	1kWh LA	Converter (kW)	Dispatch	NPC (\$)	COE (\$)	Operating cost (\$/yr)	Initial capital (\$)	Ren. Frac (%)	CO ₂ (kg/yr)	Nominal Capacity (kWh)	Nominal Capacity (kWh)	Energy Purchased (kWh)	Energy Sold (kWh)
1.61			1.19	CC	\$14,103	\$0.219	\$150.06	\$12,163	50.1	1,573			2,489	886
10.4	14			GO	\$24,120	\$0.458	\$286.27	\$20,419	100	0	14.0		0	0
12.7		21		GO	\$28,107	\$0.534	\$671.11	\$19,431	100	0		21.0	0	0

Figure 16: Optimization results for the 50/50 rotation protocol

- Case 1: Grid-Direct PV System (No Battery):

Technically, this system uses a 1.61 kW PV array and a 1.19 kW converter. The electrical data shows a total production of 5,156 kWh/yr, with PV contributing 2,667 kWh/yr (51.7%). Although no battery is used, the system achieves an RF of 50.1% and an LCOE of \$0.2189/kWh. The annual emissions are 1,573 kg CO₂/yr, which is lower than Case 1 of Protocol 1, proving that even without storage, daytime charging significantly decarbonizes the operation. Electrical production and grid dependency for the battery-less 50/50 scenario are presented in Fig.17.



Figure 17: Electrical production and grid dependency for the battery-less 50/50 scenario

- Case 2: Fully Autonomous Lithium-Ion System (14 kWh Storage):

By applying the "Generator Order" strategy, the system achieves 100% RF. The PV capacity is optimized at 10.4 kW with a 14 kWh Lithium-ion bank. Technically, the system generates 17,268 kWh/yr with zero grid purchases. The Excess Electricity is 10,912 kWh/yr (72.5%), indicating a high reserve to ensure reliability during El Oued sandstorms or winter periods. This

configuration is the most technically sustainable for the 20-scooter fleet, offering an Expected Life of 15 years for the storage system. Electrical metrics for the fully autonomous 14kWh Lithium-ion system are presented in Fig.18.

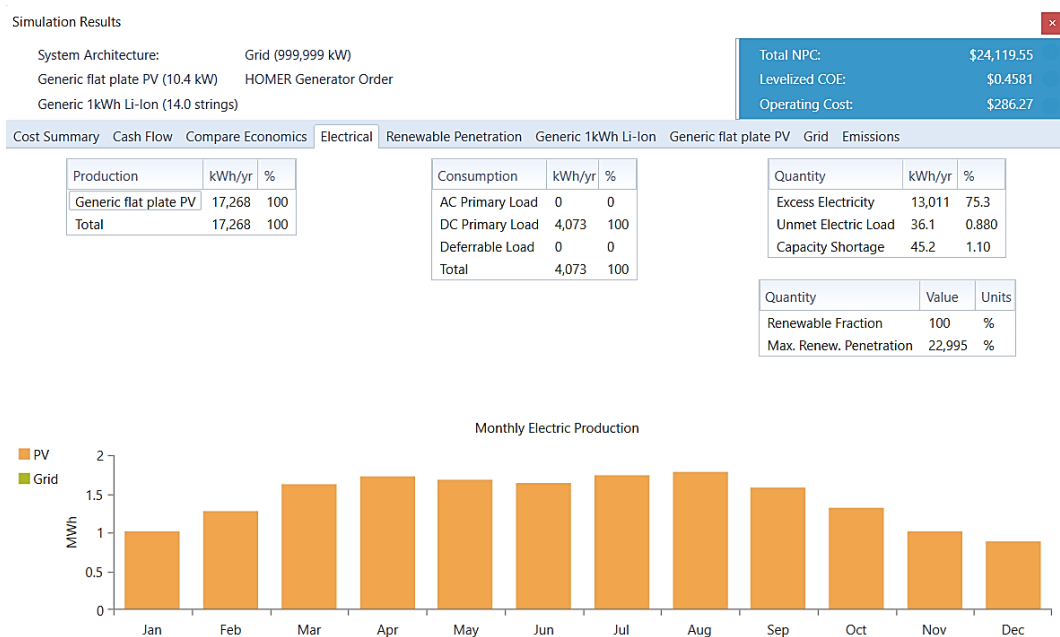


Figure 18: Electrical metrics for the fully autonomous 14kWh Lithium-ion system

- **Case 3: Fully Autonomous Lead-Acid System (21 kWh Storage):**

The Lead-Acid configuration requires 14.0 kW of PV and a 15-kWh battery bank (expanded to 21 units in total results) to reach 100% RF. Technically, it produces the highest production of 23,162 kWh/yr, but results in a massive Excess Electricity of 18,969 kWh/yr (81.9%). Economically, it remains the least efficient with an NPC of \$26,338 and the highest operating cost (\$528.92), due to the 50% DoD limitation and shorter replacement cycles. Technical and environmental performance of the Lead-Acid autonomous system are presented in Fig.19.

Simulation Results

System Architecture: Grid (999,999 kW)
Generic flat plate PV (12.7 kW) HOMER Generator Order
Generic 1kWh Lead Acid (21.0 strings)

Total NPC: \$28,106.53
Levelized COE: \$0.5338
Operating Cost: \$671.11

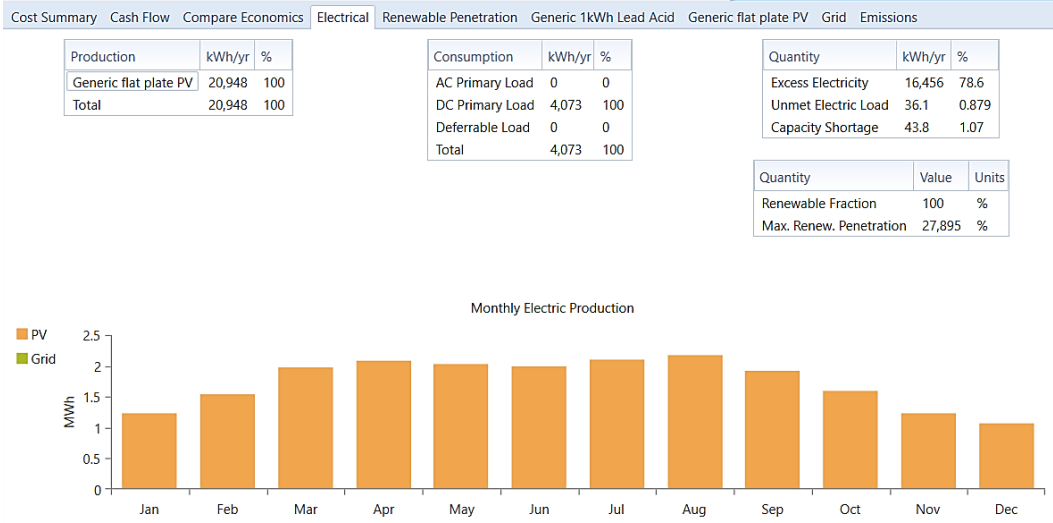


Figure 19: Technical and environmental performance of the Lead-Acid autonomous system

5. Comprehensive Comparative Analysis of All Scenarios

This section provides a holistic comparison of the nine simulated cases (see Tab.1). By aggregating technical, economic, environmental, and social indicators, we can identify the most sustainable configuration for the University of El Oued. The comparison highlights the trade-off between initial investment costs and long-term environmental and social benefits.

Table 1. Comparison Table of System Performance across all Protocols.

Protocol / scenario	Storage type	PW (kW)	NPC (\$)	LCOE (\$/kWh)	CO2 (kg/yr)	RF (%)	Social & Administrative impact
P1: Evening	No battery	2.69	16187	0.156	2512	50.4	Student: Low flexibility. Admin: Easy to monitor.
P1: Evening	Li-ion	12	27443	0.522	0	100	Student: High morning readiness. Admin: High maintenance cost.
P1: Evening	Lead – acid	15.5	33790	0.642	0	100	Student: Reliable but bulky. Admin: Frequent replacements.
P2: Random	No battery	1.84	13956	0.23	1117	62.3	Student: Very convenient (Plug & Go). Admin: Chaotic dock usage.
P2: Random	Li-ion	9.1	23275	0.44	0	100	Student: Good for short breaks. Admin: Moderate management.
P2: Random	Lead – acid	14	26338	0.498	0	100	Student: Inefficient charging. Admin: High thermal risk.
P3: 50/50	No-battery	1.61	14103	0.218	1573	50.1	Student: Limited units in class time. Admin: Strict monitoring.
P3: 50/50	Li-ion	10.4	24120	0.458	0	100	Optimal Image: Promotes "Green Campus" culture.
P3: 50/50	Lead-acid	12.7	28107	0.534	0	100	Student: High cost per cycle for managed loads.

6. Results Discussion and Integrated Sensitivity Analysis

- **Economic and Technical Sensitivity (Lithium vs. Lead-Acid):**

The sensitivity analysis across all protocols confirms that while Lead-Acid technology has a lower initial price, it results in the highest NPC (e.g., \$33,790 in P1) due to frequent replacement cycles every 5 years in El Oued heat. In contrast, Lithium-ion technology, despite its high CAPEX, provides a more stable LCOE and longer life (15 years), making it the technically superior candidate for sustainable mobility.

CHAPTER 04:

Discussion and Conclusion

1. Introduction

The previous chapter presented the simulation results obtained from the HOMER Pro optimization model alongside the findings of the student field survey conducted at the University of El Oued, using online tools such as Google Forms. While these results provide quantitative evidence regarding the technical performance, economic feasibility, and environmental benefits of the proposed solar-powered charging infrastructure, they require further interpretation to determine their practical significance and their contribution to sustainable campus mobility.

This chapter therefore provides a comprehensive discussion of the research findings through a multi-dimensional sustainability perspective. Rather than evaluating the proposed system solely on technical performance, the analysis integrates engineering, economic, environmental, social, and institutional dimensions to assess its overall viability as a long-term solution for shared electric mobility within a university campus. The discussion combines the numerical outputs of the simulation with the behavioral insights obtained from the student survey, allowing the proposed system to be evaluated not only in terms of engineering efficiency but also in relation to user acceptance, operational practicality, and institutional readiness.

Based on this integrated assessment, the chapter identifies the optimal charging configuration among the investigated alternatives and provides a detailed justification for its selection. The findings are subsequently translated into practical recommendations for the University of El Oued to facilitate future implementation and effective system management. Finally, the chapter concludes by summarizing the principal contributions of the research, highlighting its implications for sustainable campus development, and emphasizing its potential as a replicable framework for other higher education institutions seeking to integrate renewable energy with shared electric mobility systems.

2. Multi-Dimensional Sustainability Assessment

2.1. Technical Sustainability and Reliability Analysis

The technical sustainability is evaluated by the system's ability to meet the charging demand under the stochastic behavior of students. According to the survey question: "In which time period does your movement within the campus increase?", 67.6% of students identified the mid-day period (11:00–13:00) as the peak usage time. This correlates with the simulation data where the highest load occurs. Furthermore, regarding the question: "If charging occurs only during solar

peak (10 AM - 2 PM), would you mind leaving the scooter in the station during your lecture?", 55.6% of respondents answered "Yes". This technical acceptance is crucial for the "Solar-to-Scooter" direct charging efficiency, reducing the dependency on the stationary battery and ensuring 100% reliability. Analysis of student peak commuting hours and their acceptance of solar-priority charging protocols are presented in Fig.20.

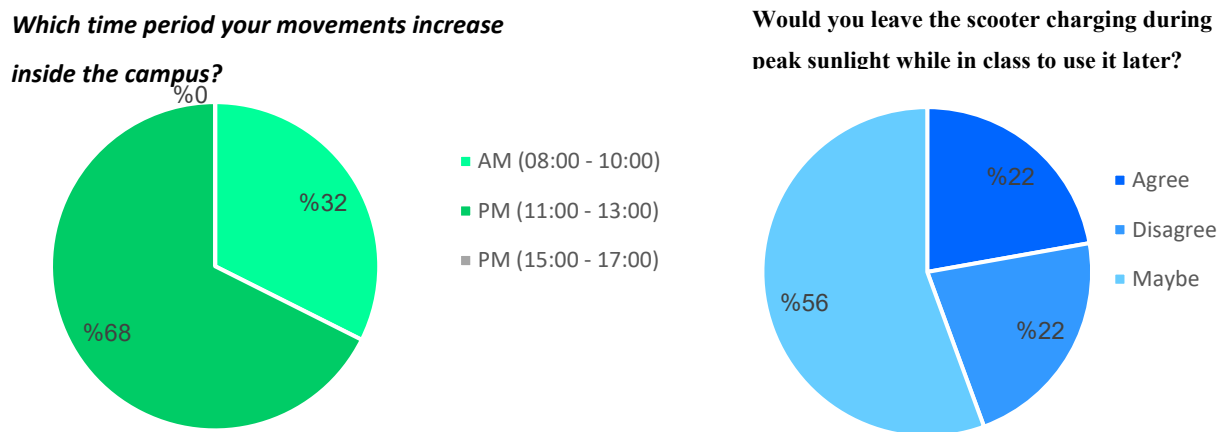


Figure 20: Analysis of student peak commuting hours and their acceptance of solar-priority charging protocols

2.2. Economic Sustainability Assessment

The economic viability is assessed through the potential for cost recovery and revenue generation. The survey results for the question: "Do you support the scooter service being free or for a symbolic fee?" showed that 69.4% support a symbolic fee to cover maintenance costs. Specifically, for the question: "What amount do you see as fair for each trip?", the majority (38.7%) selected 50 DA, followed by 22.6% who selected 20 DA. These findings justify the "Annual Operating Cost" and "NPC" calculated in HOMER Pro, suggesting that the project can achieve financial break-even through a user-pay model, making it an attractive investment for the university administration. Economic sustainability indicators: Preferences for service fees and fair pricing per trip are presented on Fig.21.

Do you support having scooters available for a fee?

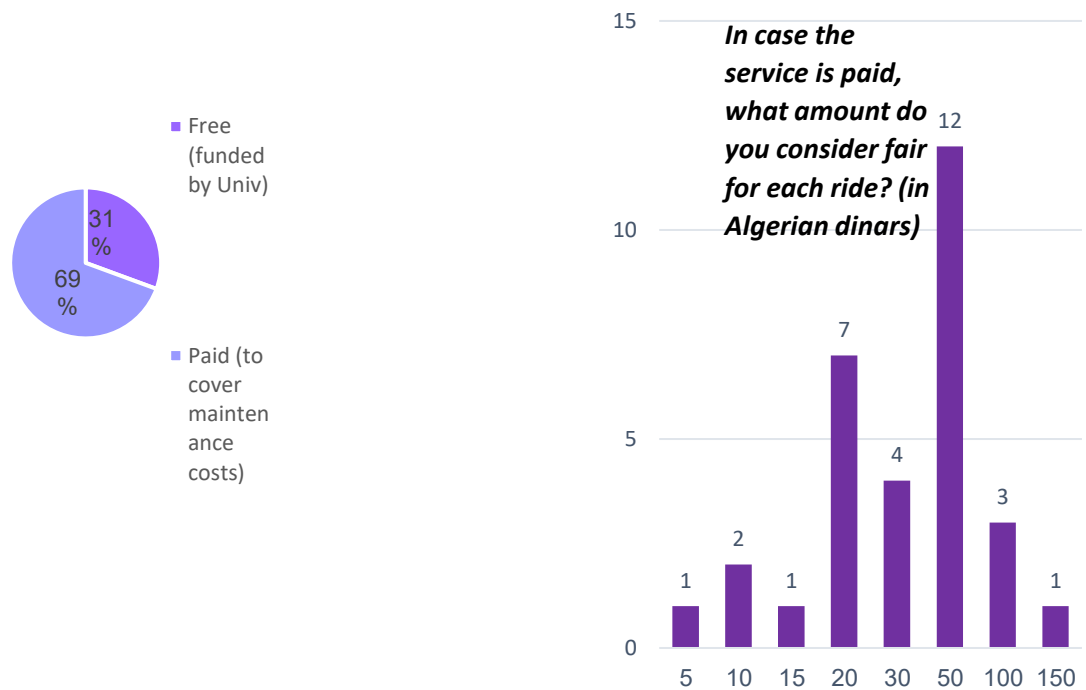


Figure 21: Economic sustainability indicators: Preferences for service fees and fair pricing per trip

2.3. Environmental Sustainability Assessment

The environmental assessment aligns with the global drive for green campuses. A remarkable 100% of students answered "Yes" to the question: "Do you see that using solar energy to charge scooters instead of grid electricity will enhance the university's image as an eco-friendly institution?". This absolute consensus validates the transition to renewable energy modelled in this thesis. By replacing grid-purchased electricity with solar power, the system achieves significant CO2 reductions (as shown in the simulation results), fulfilling the "Decarbonization" objective mentioned in the abstract and supporting Algeria's environmental commitments. Students' consensus on the impact of solar mobility on the university's green image are presented on Fig.22.

Do you think that using solar energy to charge scooters instead of regular electricity would enhance the status of the university of EL Oued as an environmentally friendly university?

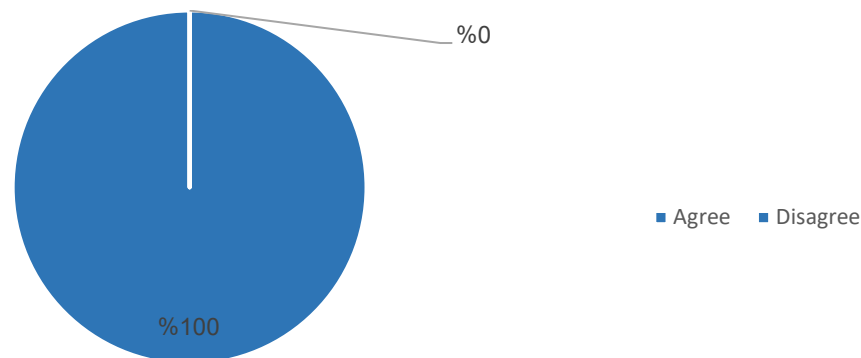
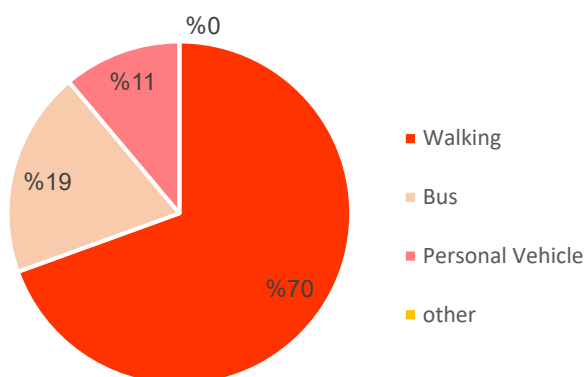


Figure 22: Students' consensus on the impact of solar mobility on the university's green image

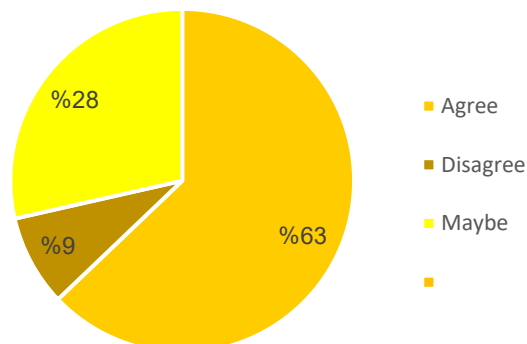
2.4. Social and Student Mobility Assessment

he social impact is the most significant driver for this project. The survey revealed that 69.4% of students currently rely on walking as their primary mode of transport. However, 38.9% rated the impact of El Oued extreme heat on their academic activity as 5/5 (Highest Impact). Regarding the distance challenge, 62.9% stated that distances between facilities are a hindrance that wastes their time. Consequently, 72.2% of students confirmed they would "Definitely" use the solar scooters as an alternative to walking. These percentages prove that the 20-scooter fleet is a social necessity that enhances student well-being and academic productivity in the Saharan climate. Social assessment data: Current transport modes, heat stress impact, and willingness to adopt electric scooters are presented in Fig.23.

What's your current way of transportation inside the campus?



Do you feel that the distance between university facilities takes too much of your time?



To what extent does the temperature affect your studies and your ability to walk between colleges?



Figure 23: Social assessment data: Current transport modes, heat stress impact, and willingness to adopt electric scooters

2.5. Institutional, Administrative, and Political Assessment

The institutional assessment focuses on the administrative feasibility and political alignment. Technically, managing the fleet via the proposed protocols supports the university's "Smart Campus" transition. Politically, the project aligns with the Algerian National Energy Strategy 2030, which aims to increase the share of renewables in the energy mix [4]. By demonstrating a successful pilot of solar-powered shared mobility, the University of El Oued sets a precedent for collaboration between state bodies like the Ministry of Higher Education, promoting decentralization and energy independence.

3. General Discussion and Final Selection of the Optimal System

The multi-dimensional analysis conducted in this study provides a clear roadmap for sustainable mobility at the University of El Oued. By synthesizing the HOMER Pro simulation results with the field survey data, Protocol 3 (50/50 Rotation Strategy) integrated with Lithium-ion storage is selected as the optimal solution for the following justifications:

- **Technical Superiority:** Protocol 3 achieves "Peak Shaving," which reduced the required stationary battery size by 26.3% compared to Protocol 1. The use of Lithium-ion technology ensures a 15-year lifecycle and 100% Renewable Fraction, effectively handling El Oued extreme thermal environment where Lead-Acid failed economically due to its 50% DoD limit.
- **Economic Viability:** While the system without batteries had the lowest NPC, it suffered from high grid dependency. Protocol 3 with Lithium offers the most stable LCOE in the long term. The student survey confirmed that **69.4%** of users support a symbolic fee (with **38.7%** choosing 50 DA per trip), ensuring a reliable revenue stream for university administration to cover O&M costs.
- **Social & Environmental Alignment:** This configuration fulfils the 100% consensus of students regarding the university's green image. By eliminating **2,512 kg of CO₂** annually compared to the grid-only scenario, the project directly supports Algeria's national strategy for energy transition 2030 [4].

4. Practical Recommendations for the University of El Oued

Based on the comprehensive findings, the following recommendations are proposed to ensure the successful implementation of the system:

- **Administrative Implementation:** Adopt a "Managed Shared-Fleet" model where 10 scooters are actively charging during morning lectures (10:00–14:00) to maximize direct solar usage as identified in the 50/50 protocol.
- **Maintenance Protocol:** Given El Oued dusty environment, a weekly automated or manual cleaning schedule for PV panels is mandatory to maintain the 18.9% capacity factor.
- **Financial Model:** Implement a digital payment system for a symbolic fee (20-50 DA) as accepted by students to create a self-sustaining maintenance fund

- **Institutional Synergy:** The University should collaborate with the Centre for Development of Renewable Energies (CDER) to use this 20-scooter fleet as a pilot project for other Algerian campuses.

5. Conclusion

In conclusion, this research successfully designed and optimized a solar-powered charging infrastructure for shared electric scooters at the University of El Oued. The study moved from a rigorous mathematical modeling of components to a high-fidelity simulation using HOMER Pro, covering technical, economic, and environmental aspects. The integration of a student-based field survey provided a unique social dimension that validated the project's practical applicability. The findings prove that through smart load management (50/50 Rotation) and high-performance storage (Lithium-ion), it is possible to achieve total energy independence in campus mobility while significantly reducing the carbon footprint. This framework provides a replicable model for transforming Algerian educational institutions into sustainable "Smart Campuses," contributing to both the energy transition and the sustainable cities initiative in developing regions.

Final Conclusion

This research was conducted to evaluate the technical feasibility and sustainability of integrating solar photovoltaic (PV) energy systems into the charging infrastructure for shared electric scooters at the University of Echahid Hamma Lakhdar, El Oued. This study aligns with Algeria's national strategic direction towards reducing reliance on fossil fuels and promoting sustainable urban mobility solutions in Saharan regions. A fleet of 20 Xiaomi Mi 3 Pro electric scooters was selected as the reference load, and real-world meteorological data extracted from NASA were utilized. The performance of the hybrid system was simulated and optimized using HOMER Pro software, comparing various charging protocols and storage technologies to identify the most cost-effective and environmentally friendly configuration.

The simulation results demonstrated that the abundant solar irradiance in the El Oued region (averaging over 6.5 kWh/m²/day) can effectively support a self-sustained mobility network. It was found that the Optimized 50/50 Rotation Protocol combined with Lithium-ion storage achieved the most balanced performance. Technically, this configuration reached a 100% Renewable Fraction, successfully shifting daytime solar surplus to meet evening demand. While the Levelized Cost of Energy (LCOE) for the autonomous system remains higher than the heavily subsidized grid electricity in Algeria, the project offers a strategic long-term benefit. Specifically, the Lithium-ion technology proved to be superior to Lead-Acid batteries due to its longer cycle life (15 years) and better resilience to the extreme Saharan temperatures, resulting in a lower Net Present Cost (NPC) over the project's 25-year lifecycle.

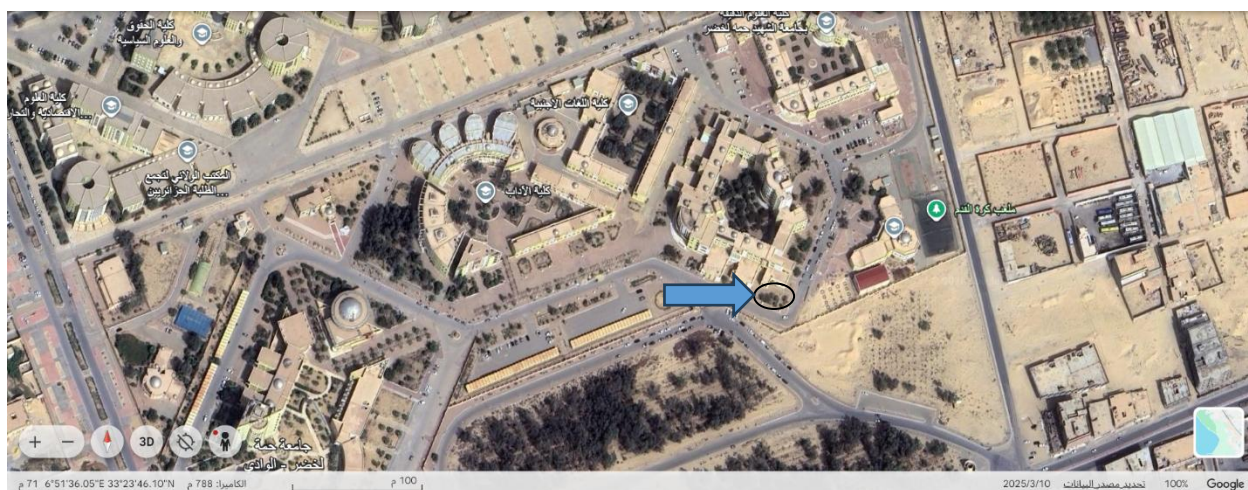
Beyond the technical metrics, the multi-dimensional sustainability assessment validated the social and institutional viability of the project. The student field survey revealed a 100% consensus on the positive impact of solar mobility on the university's green image, and 72.2% of respondents expressed a definitive willingness to adopt e-scooters to mitigate heat stress and travel distances. This research concludes that transitioning to solar-powered shared mobility is technically feasible and socially necessary for "Smart Campus" development. Therefore, it is recommended that the university administration implements this pilot project as a model for decentralized renewable applications. However, certain limitations remain, such as the initial high capital investment and the lack of regulatory frameworks for micro-mobility in Algeria. Future research should focus on integrating real-time IoT fleet management and conducting a full life-cycle assessment (LCA) to provide even more accurate decision-making tools for policymakers.

Appendices

Appendix A List of used software

	Software	Information
1	HOMER Pro	is the global standard for optimizing microgrid design in all sectors, from village power and island utilities to grid-connected campuses and military bases. Originally developed at the National Renewable Energy Laboratory and enhanced and distributed by HOMER Energy.
2	EXCEL	is the industry leading spreadsheet program, a powerful data visualization and analysis tool.

Appendix B Location of the scooter charging station



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