Mixed Energy Architecture in Industry: Integration of LV/HV Networks and Photovoltaic Production in a Tunisian Context.

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DOI : https://doi.org/10.51584/IJRIAS.2025.100800152

Received: 24 August 2025; Accepted: 29 August 2025; Published: 29 September 2025

SUMMARY

We are now operating in a context where managing energy consumption is becoming a necessity, both from an environmental and economic point of view. Controlling this consumption is essentially based on the appropriate choice of electrical components (cables, transformers, circuit breakers, relays, etc.), their optimal installation, as well as the general maintenance measures to be adopted [1]. The objective is to guarantee, as far as possible, the safety of the installed equipment and, above all, that of the people likely to access it. As part of this study, we will detail the different methodological stages necessary to achieve an optimal electrical design of our industrial installation. [2, 3].

The constant increase in electricity consumption in industrial sectors encourages the rethinking of electrical installations, both in low voltage (LV) and high voltage (HV). This work is part of a project carried out at the SNCFT management of Borj Cédria in the Tunisian context and aims to study, design and integrate a high-performance electrical solution, incorporating both conventional technologies (TGBT, transformers, protections) and innovative solutions (photovoltaic, reactive energy compensation) [4]. The study demonstrated the technical and economic feasibility of such a project in a Tunisian context.

Keywords : Energy architecture, electrical energy, photovoltaic solar energy, Tunisian context.

INTRODUCTION

Renewable energy sources are numerous, but among the most promising are wind and solar energy. Regarding the latter, although only a tiny fraction of solar radiation reaches the Earth's surface, the incident energy available each year is estimated to be more than six thousand times the annual global electricity consumption. According to available data, the installed capacity of photovoltaic production worldwide stood at 5.2 GW in 2006, with projections reaching 1000 GW by 2030 [5].

Many countries have invested heavily in the development of solar energy, including France, Spain, Germany, and Japan, among others. In comparison, Tunisia remains at a modest stage in terms of deploying this technology [6].

This work, carried out within the Tunisian National Railways Company (SNCFT), aims to explore the potential for integrating renewable energies into industrial installations [7,8].

Electrical energy is the lifeblood of all industrial activity. In a context of continually increasing needs and energy transition objectives, the modernization of electrical installations is essential. The project presented concerns the study and design of a low-voltage/high-voltage installation in a railway factory, with the integration of photovoltaic solar energy and reactive energy compensation.

CONTEXT AND PRESENTATION OF THE COMPANY

Presentation of the Tunisian National Railway Company (SNCFT)

The Tunisian National Railway Company (SNCFT) is a public industrial and commercial institution, under the supervision of the Ministry of Transport. It manages, operates, and maintains the national railway network, which consists of 23 lines, totaling 2,153 km and serving approximately 200 stations. This network allows the transport of passengers (main lines and suburbs) as well as goods, mainly phosphates (approximately 75% of freight).

The network is divided into two sections according to track gauge: the northern part uses standard gauge (1,435 mm), while the southern part is metre gauge (1,000 mm). It is connected to the Algerian network via the Ghardimaou border crossing.

Created by decree on December 27, 1956, the SNCFT initially took charge of the northern network. The southern network, previously operated by the Compagnie des phosphates et des chemins de fer de Sfax-Gafsa under a concession dating from 1897, was integrated into the SNCFT in 1967, upon the expiration of the said concession.

As part of its modernisation strategy, in 2007 the SNCFT acquired ten new trains for high-traffic lines (Tunis–Sousse, Tunis–Sfax), and launched a major electrification project for the Tunis–Borj Cédria section, with entry into service initially planned for 2009. This project includes the order of twenty trains and infrastructure work carried out by the companies Hyundai Rotem, Sumitomo Corporation, Alstom and Ansaldo.

The average train frequency is 20 minutes, with a drop to 5 minutes during rush hour. Electrification aims to improve network performance, reducing journey times from 48 to 37 minutes. The program also includes investments of more than 200 million dinars for the addition of tracks, the automation of traffic control, the construction of a maintenance workshop, and the development of safe level crossings.

Despite initial optimistic planning, the commissioning of the electrified line was postponed several times, falling five months behind the planned date of April 2011.

Problem

The plant's current electrical installation has several shortcomings that directly affect its energy efficiency and overall performance. These shortcomings are mainly reflected in unstable and high energy consumption, a low power factor (cos $\varphi < 0.85$), as well as a total lack of integration of renewable energy into the energy system.

Unstable and excessive energy consumption

An analysis of electrical loads reveals significant variability in energy consumption across the various production facilities. This instability is largely due to unbalanced load distribution, a lack of an energy management system, and unoptimized use of equipment. In addition, some machines are obsolete or poorly sized, which increases energy losses and reduces the efficiency of the entire internal electrical network.

Low power factor (cos φ)

A power factor below 0.85 indicates a significant presence of reactive power in the network, which leads to overloading of distribution equipment (transformers, cables, circuit breakers, etc.) and an increase in Joule losses. This situation affects the quality of the power supply and also results in financial penalties imposed by the electricity supplier. Correcting this power factor through the installation of capacitor banks or dynamic compensation systems is therefore essential to optimize network performance.

Lack of renewable energy

Despite the region's high solar potential, no renewable energy sources are currently being exploited within the facility. This situation represents a shortfall in terms of energy autonomy, reduction of electricity bills, and contribution to the energy transition. Lighting administrative buildings represents a viable opportunity for the introduction of photovoltaic systems, which would partially cover electrical needs while reducing the load on the main grid.

Objectives related to the problem

Faced with this situation, this work aims to:

- Diagnose and analyze the weak points of the current electrical system;
- Propose solutions for stabilizing energy consumption;
- Implement a power factor improvement strategy;
- Study the feasibility of integrating a photovoltaic system for administrative lighting.
- Establish the power balance of the installations.
- Propose an optimized electrical architecture in HV and LV.
- Sizing a stand-alone photovoltaic system for administrative lighting.
- Improving power factor through reactive compensation.

These actions are part of an energy efficiency and sustainable development approach, in accordance with the technical, economic and environmental requirements of the industrial sector.

Needs analysis and inventory

Workshops and offices

The SNCFT industrial facility comprises several functional areas, including maintenance workshops, storage areas (stores), and specialized facilities such as the pit tower. These areas are supplied with electrical power to operate various equipment essential to production, maintenance, and management activities.

The main equipment listed is:

- **Electric motors** with a maximum individual power of up to 37 kW (used for compressors, overhead cranes, etc.);
- **More than 600 light points**, composed of fluorescent tubes (neon type) with electromagnetic ballast;
- **25 air conditioners distributed** in offices and control rooms;
- **Computers, printers and IT equipment**;
- **Industrial air compressors** and other specialized electrical tools.

These installations often operate in an uncoordinated manner, resulting in irregular power demands and reduced energy efficiency.

Installed power

The estimated installed power in the administrative building indicates a value of 11,495 W, or approximately 11.5 kW. This power includes:

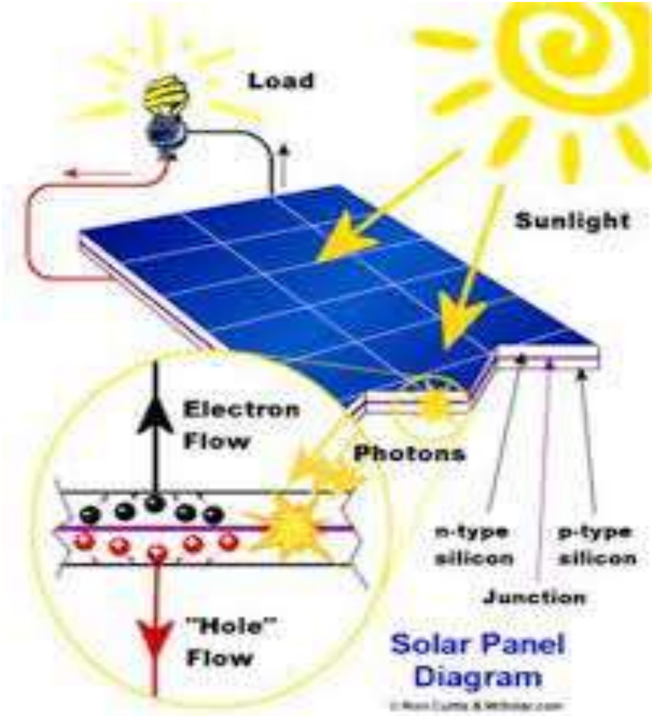
- Lighting (neon and LED tubes);
- Wall-mounted air conditioners;
- Office and communication equipment;
- Auxiliary devices (water heaters, LAN networks, etc.).

This power is theoretical and must be corrected by simultaneity factors for realistic sizing.

Integration of photovoltaics

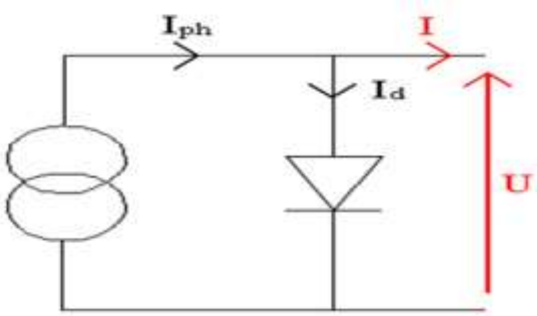
Photovoltaic energy and capacitor batteries are different technologies in form and substance, each of these technologies Found for a particular use and for a well-defined function, for this There must be a good knowledge of these two technologies [9].Photovoltaic solar energy is a form of renewable energy. It produces electricity by transforming part of the sun's rays using a photovoltaic cell.

Figure 1: Design of photovoltaic systems [10]



The behavior of the photovoltaic cell is comparable to a direct current generator to which a diode is added, in accordance with figure (2). In fact, the electric field makes the space charge zone (SCM) a diode which only allows current to pass in one direction.

Figure 2: Ideal diagram of a photovoltaic cell [11]



The current at the cell terminals is:

$$I = Iph - Id$$

Iph: is the current generated by the illumination; it is also called photocurrent. We will show later that it is always proportional to the illumination.

Id: current flowing through the diode, also called dark current.

$$Id = Is^{*}[exp(\frac{V}{UT}) - 1]$$

UT: thermal tension

V = U: voltage across the diode terminal.

$$I(v) = Iph - Id = Iph - Is^{*}[exp(\frac{V}{UT}) - 1]$$

After providing a general overview of the various configurations of photovoltaic installations, we focused on the key components of a stand-alone photovoltaic system. These include photovoltaic modules, storage batteries, charge controllers, matching devices, DC/DC and DC/AC converters, and protection equipment. Particular attention was paid to the essential elements of batteries and energy converters, due to their decisive role in the reliability and overall performance of the system.

Following on from this theoretical analysis, the following parts will be devoted to the study of the technical dimensioning and economic evaluation of an autonomous photovoltaic installation adapted to the industrial context studied.

SIZING OF A STAND-ALONE PHOTOVOLTAIC SYSTEM

Sizing a photovoltaic (PV) system is a crucial step that aims to ensure the adequacy between solar energy production and the actual energy needs of an installation. It is based on detailed modeling of environmental parameters (sunshine, temperature, orientation) and technical parameters (load profile, component efficiency, autonomy, energy losses). The objective is to guarantee the continuity of the power supply while optimizing the overall investment cost.

The sizing of a PV system consists of determining, based on the sunshine and the load profile, all the elements of the PV chain, namely the power of a converter, the electricity requirement and the solar deposit, which constitute the inputs of the problem to be solved. The dimensional study will be based on two PV generators (NU- E235(E) 235Wc and JYM210) available within the two company's SES and Tunisia Energy.

Input parameters for dimensioning

The sizing of a stand-alone PV system depends mainly on the following parameters:

- **The electric charge profile**: This is the variation in electricity consumption over time (hours of the day, days of the week, seasonality). It is defined in kWh/day and determines production and storage capacity.
- **The solar deposit**: Local sunshine data expressed in kWh/m²/day. For the northern region of Tunisia, particularly in Borj Cédria, the average annual irradiation exceeds 5 kWh/m²/day, with an estimated minimum value of 4.03 kWh/m²/day in December, used as a calculation basis for critical situations.
- **Overall losses**: Include efficiency losses due to regulators, converters, cables, panel tilt, shading, temperature, etc. These losses are generally increased by 20 to 30%.
- **The desired autonomy**: Number of days the installation can continue to operate without solar input (often between 2 and 5 days). This determines the capacity of the batteries.
- **The type and characteristics of the components**: Including PV modules, charge regulators, batteries and converters, whose performance directly influences system reliability.

Selection and characterization of photovoltaic generators

Two types of generators were selected for this study, available from local suppliers (Tunisie Énergie and SES):

Module JYM210 (Tunisia Energy)

- Peak power: 210 Wc

ISSN No. 2454-6194 | DOI: 10.51584/IJRIAS |Volume X Issue VIII August 2025

- No-load voltage: 52.9 V
- Short circuit current: 5.18 A
- Module efficiency: approximately 15.5%
- Unit area: 1,537 m²

NU-E235(E) 235Wc (SES) module

- Peak power: 235 Wc
- Open circuit voltage: 37.0 V
- Short circuit current: 8.60 A
- Module efficiency: approximately 17.2%
- Unit area: 1,642 m²

The number of modules required (Nm) is obtained according to the relationship:

Nm=P m / P total peak

Where: Ptotal peak is the required power corrected for losses (e.g.: 16 kWc) and Pm the nominal power of the module.

Determination of the occupied surface area

The total area required for installing the modules is determined by:

S=N m × S module

The areas that can be occupied by PV modules are given in Table 1.

Table 1: The area occupied by PV.

	Tunisia energy	HIS
Surface area per module	1,537m2	1,642 m2
Number of modules	78	70
Total field area	119.88 m2	114.94 m2

Climatic conditions and inclination

The climatic characteristics of northern Tunisia, marked by strong annual irradiation, offer particularly favorable solar potential.[12]. The optimal inclination of the panels, to maximize the annual capture of radiation, is estimated between 30° and 45°, with a compromise at 45° for better performance in winter.

Given the favorable climatic characteristics in the North of the country, it has been noted that the use of the photovoltaic generator with storage system is a practical solution, it is even expected to become, in a few years, an essential alternative for the vitality of the national economy.

Considering sensors of width h, the center distance of the rows of sensors is:

hx (cos 45° + sin 45°/tg16°) = b.

- h = sensor dimension.
- α = minimum solar height (generally taken on December 21, i.e. an angle of 16°).

ISSN No. 2454-6194 | DOI: 10.51584/IJRIAS |Volume X Issue VIII August 2025

- β = 45°.
- b =PV spacing

Table 2: PV Spacing and Inclination

	Tunisia energy	HIS
The angle of inclination	45°	45°
PV spacing	4.76 m	5.21 m

Painting1Spacing and TiltPV

Justification for choosing a stand-alone system with storage

The choice of an autonomous photovoltaic system with batteries is essential in this context for several reasons (figure 3):

- **Partial independence from the national network**, which increases the energy resilience of the industrial site.
- **Reduction of consumption peaks**, especially during the day, thanks to buffer storage.
- **Contribution to the national energy transition strategy**.
- **Gradual reduction of the energy bill** (depreciation over 6 to 7 years).

This type of system, adapted to the demand for lighting and light power, fits perfectly with sustainable development objectives and could, in the long term, be extended to other uses (air conditioning, automation, etc.).

Figure 3: Overall process of sizing a system stand-alone photovoltaic.

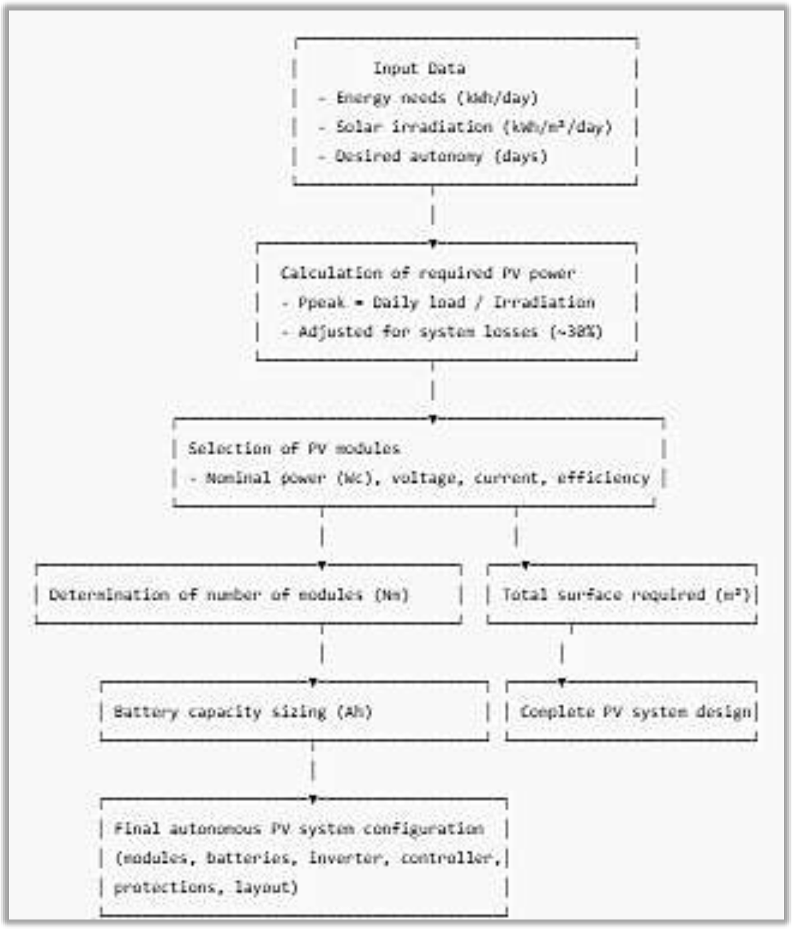


Table 1: Technical comparison of the two photovoltaic generators studied

Features	JYM210 (Tunisia Energy)	NU-E235(E) (SES)
Peak power (Wp)	210 W	235 W
Open circuit voltage (Voc)	52.9 V	37.0 V
Short-circuit current (Isc)	5.18 A	8.60 A
Estimated yield (%)	≈ 15.5%	≈ 17.2%
Unit area (m²)	1,537 m²	1,642 m²
Number of modules (estimated)	78	70
Total area required (m²)	119.89 m²	114.94 m²

The LV/HV integration project, coupled with photovoltaic production and reactive compensation, offers a robust, sustainable, and economically viable technical solution. It is fully in line with Tunisia's energy transition strategies and can serve as a replicable model for other industrial sites.

CONCLUSION

This work is part of an integrated energy optimization strategy, aiming to reconcile technical performance, economic viability and environmental sustainability, through the design and dimensioning of an autonomous photovoltaic system applied to a real industrial context. The study, carried out within the management of the SNCFT of Borj Cédria in Tunisia, made it possible to systematically explore the multiple facets of a solar energy electrification project, from the characterization of the energy need to the proposal of a hybrid electrical architecture combining LV/HV networks and photovoltaic production.

On a scientific level, the objectives set were achieved using a rigorous methodology, structured around several axes:

- **Preliminary energy analysis**enabled a relevant diagnosis to be made of the existing situation, highlighting critical malfunctions, such as unstable consumption, low energy efficiency and a lack of reactive compensation, all responsible for significant technical and financial losses.
- **The review of energy sources**contextualized the strategic interest of solar photovoltaics in the Tunisian energy mix, highlighting the untapped potential of local solar irradiation as a vector of energy transition.
- **The in-depth study of photovoltaic cells**, based on the foundations of semiconductor physics, has made it possible to identify the key performance parameters (form factor, efficiency, threshold voltage, temperature effects, etc.), necessary for faithful modeling of solar generators.
- **Detailed technical sizing**of the installation (PV modules, converters, storage batteries, regulators and protections) was carried out according to current standards, taking into account overall losses, the load profile and local climatic conditions, thus ensuring an optimal match between production and demand.
- **Integration of reactive energy compensation**was designed as a lever for improving the power factor, helping to reduce overloads in distribution networks, to optimize the use of transformers and to minimize losses due to the Joule effect.
- **Comparative technical-economic assessment**, based on real quotes from local suppliers, made it possible to demonstrate the potential profitability of the project, with an estimated return on investment in the medium term (6 to 7 years), thus consolidating its feasibility in a Tunisian industrial context.

This project therefore goes beyond the purely technical and economic dimension to propose an intelligent and scalable energy architecture, adaptable to other industrial sites. It constitutes an operational prototype of the energy transition in an industrial environment, combining the reliability of conventional electrical infrastructures with the flexibility of decentralized renewable sources.

In a global context characterized by the scarcity of fossil resources, the volatility of energy prices, and the imperatives of decarbonization, the implementation of autonomous photovoltaic systems in Tunisian industrial infrastructures appears not only as an opportunity, but as a strategic necessity. The results obtained in this work confirm that the adoption of hybrid energy solutions, technically well-sized and integrated into the existing electrical architecture, is a realistic, sustainable and economically viable way to improve the energy efficiency and resilience of industrial systems.

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