International Journal for Multidisciplinary Research (IJFMR)

E-ISSN: 2582-2160 ● Website: www.ijfmr.com ● Email: editor@ijfmr.com

Scientific Approach for the Deployment of a 300 KWP Residential PV System: Modeling, Simulation and Environmental Impact

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ABSTRACT

This article presents a comprehensive approach for the design, sizing, and evaluation of a 300 kWp photovoltaic installation integrated into a residential roof and connected to the STEG grid. Based on the objectives of the Tunisian Solar Plan, the STEG specifications, and the geographical constraints of Tunisia, the study combines theoretical analyses, advanced modeling, and simulation using PVSyst to ensure a system that is efficient, safe, and compliant with international standards.

The detailed methodology covers:

- the choice of solar modules (technology, power, temperature coefficients) and inverters (maximum efficiency, voltage and current ranges)
- the definition of field-inverter architectures (centralized vs. string) and the calculation of series/parallel configurations
- the sizing of cables and protective devices (fuses, surge arresters, differential devices) according to IEC 61215, IEC 61730, IEEE 1547 and IEC 61724
- the implementation of dual-diode simulation and maximum power point tracking (MPPT by incremental conductance) algorithms

PVSyst simulations integrate local irradiation profiles, thermal conditions, and system losses to estimate the performance ratio (PR) and annual production level. The economic analysis details the overall cost, the LCOE (Levelized Cost of Energy), and the payback period, taking into account STEG subsidies, ANME grants, and international financing mechanisms.

The results highlight:

- A performance ratio greater than 80% in the chosen configuration
- A competitive LCOE compared to STEG residential rates
- A repayment period of less than 8 years
- A significant reduction in CO_2 emissions over the lifetime of the project

This study demonstrates the technical feasibility and economic viability of a 300 kWp PV plant in a Tunisian residential environment, while providing a reproducible framework for other projects of similar size.

Keywords: photovoltaic, sizing, STEG, PVSyst, LCOE, performance ratio.

1. INTRODUCTION

Faced with the growing challenges of climate change, the depletion of fossil resources, and the continued rise in energy demand, Tunisia is firmly committed to a transition to a more sustainable energy future. Endowed with exceptional solar potential—with average annual sunshine reaching 1,700 kWh/m²—the country is strategically positioned to harness photovoltaic (PV) energy as a key lever for energy diversification. In this context, the Tunisian Solar Plan (PST), initiated by the National Agency for Energy Management (ANME) and supported by the Tunisian Electricity and Gas Company (STEG), constitutes an ambitious roadmap towards the massive integration of renewable energies into the national energy mix.[1].

STEG, as a central player in the Tunisian electricity grid, imposes strict technical requirements for any photovoltaic installation injected into its network. These requirements, particularly those concerning power quality, differential protection devices, safety cut-off mechanisms, and bidirectional metering, aim to ensure the stability, security, and reliability of the network, while protecting users' equipment.

It is in this demanding, yet opportunity-filled context that this project is taking place: the sizing of a 300 kWp photovoltaic power plant, integrated into a residential roof and designed to be connected to the STEG network. The installation aims to combine energy performance, compliance with international standards and economic viability, based on a rigorous methodology and advanced simulation tools.[2,3].

2. LITERATURE REVIEW AND CONTEXT

The global energy transition is driven by a growing desire to reduce greenhouse gas emissions, limit dependence on fossil fuels, and ensure equitable access to electricity. Photovoltaics, as a clean, scalable, and decentralized technology, is emerging as a strategic solution in this context.

2.1 Global context and outlook

The share of renewable energy in global electricity production increased from 13% in 1985 to 27% in 2020, according to the CNRS NOE scenario. Photovoltaics are experiencing annual growth of 20%, but remain underrepresented (0.2% of total production in 2014).

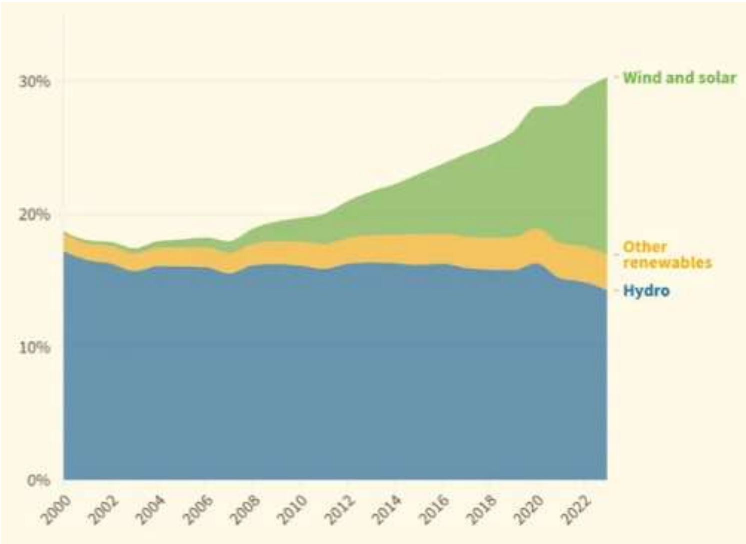

Figure 1:Growth of photovoltaics

2.2 National context

In Tunisia, the gap between electricity supply and demand reaches 15% in summer. The PST plans to install 1,500 MWp of photovoltaic power by 2030, with a total investment estimated at 3,369 MTD. Incentives include a FIT tariff and a STEG bonus of 30% of CAPEX (Table 1).

Table 1: Technology balance sheet

Technology	Yield (%)	Surface area (m²/kWc)	Lifespan (years)	Cost (€ / Wc)
Monocrystalline	18–22	4.5–5.6	25–30	0.30–0.35
Polycrystalline	15–17	6.0–6.7	25–30	0.25–0.30
Bifacial (mono)	20–24	4.2–5.0	25–30	0.35–0.40
Amorphous	8–10	10–12.5	15–20	0.20–0.25

3. APPLICABLE REGULATIONS AND STANDARDS

3.1 STEG specifications

The Tunisian Electricity and Gas Company (STEG) imposes a set of technical criteria for any photovoltaic installation connected to its network. These requirements aim to preserve network stability, avoid disruptions, and guarantee the safety of property and people.[4].

- Maximum injection: 300 kWc (peak power)
- Frequency and wave quality: < 5% harmonic distortion
- Automatic shutdown in case of network failure (anti-islanding)
- Mandatory bidirectional counting

3.2 International standards

- IEC 61215 – Qualification of crystalline modules (thermomechanical cycles)
- IEC 61730 – Electrical safety of PV modules (class II double insulation)
- IEC 61724 – Performance monitoring (PR, yield, availability)
- IEEE 1547 – Interconnection of DERs to utility grid (anti-islanding, ride-through)[4].

4. SITE CHARACTERISTICS AND CLIMATIC CONDITIONS

4.1 Meteorological data

- Heliosat/SARAH (satellite) provides global horizontal irradiation with 5 km resolution.
- Weather file (TMY) extracted from Meteonorm for Tunis (36.8 °N, 10.2 °E).

4.2 Shading Analysis

The use of PVSyst allows the 3D shading of the surrounding building to be modeled and losses (soiling, row-shadow) to be estimated. Irradiance loss is limited to ≤ 5% by adopting a spacing of 4.5 m between rows (25° inclination).[5, 6 and 7].

5. MODELING OF PHOTOVOLTAIC CELLS

5.1 Electric model

- **Single-diode**: suitable for labeled modules, identification via Lambert–Beer method.
- **Double diode**: integrates recombination at the surface and volume, recommended for the fine analysis of low irradiances[8].

5.2 Key parameters

The performance of a PV cell depends on several electrical and thermal parameters (Table 2):

- I_{SC}, V_{OC}, α (ΔI/ΔT), β (ΔV/ΔT).

- LID (Light Induced Degradation) of 1–3% in the first week[9].
- PID (Potential Induced Degradation) controlled thanks to SPF encapsulating materials.

Table 2: Key parameters

Setting	Description
I_{SC}	Short-circuit current: proportional to irradiance
V_{OC}	Open circuit voltage: depends on temperature and material
α (ΔI/ΔT)	Thermal coefficient of current: indicates sensitivity to heat
β (ΔV/ΔT)	Thermal coefficient of voltage: impacts voltage in summer

6. TECHNOLOGICAL CHOICES

The choice of photovoltaic components is crucial to ensure the performance, durability and profitability of the installation (Table 3). This section details the selection criteria for modules, inverters and the DC/AC ratio, taking into account technical, economic and climatic constraints.

6.1 Photovoltaic modules

After analyzing the cost/performance ratio, the available roof space and Tunisian climatic conditions, the choice fell on high-performance 350 Wc monocrystalline modules.

a. Technical characteristics:

- **Technology**: Monocrystalline silicon PERC
- **Nominal power**: 350 Wc
- **Yield**: 18.5%
- **Required area**: ~5.4 m^2/kWc
- **LID Degradation**: < 1% (Light Induced Degradation)
- **PID free**: encapsulants resistant to induced voltages
- **Manufacturer's warranty**: 25 years (linear performance)

b. Justification for choice:

- **High energy density**: ideal for roofs with limited footprint.
- **Low thermal sensitivity**: better stability in summer.
- **Certified reliability**: complies with IEC 61215 and IEC 61730 standards.

6.2 Inverters

The chosen architecture is based on a string configuration with six SMA STP 50-40 inverters, each with a nominal power of 50 kVA.

a. Technical characteristics:

- Model: SMA Sunny Tripower CORE1 STP 50-40
- Nominal AC power: 50 kVA
- Maximum efficiency: 98%
- Number of MPPTs: 6 independent entrances
- MPPT algorithm: Incremental Conductance (better dynamic response than P&O)
- Integrated protection: AFCI, SPD, remote monitoring

6.3 DC/AC Ratio

The DC/AC ratio represents the ratio between the installed peak power (DC) and the nominal power of the inverters (AC). A ratio of 1.15 was chosen for this installation.

Table 3: Choice of photovoltaic components

Element	Type of protection	Standard / Reference
PV modules	Lightning arrester, fuse	IEC 61730, UTE C15-712
Inverters	Circuit breaker, disconnector	IEC 62109, NF C15-100
DC/AC cables	Double insulation, copper	TUV, IEC 60228
Grounding	Lugs, bars, stakes	IEC 60364-5-54

7. FIELD-INVERTER ARCHITECTURE

Compare the two main inverter architectures for a 300 kWp PV installation:

- **Centralized**: a single high-power inverter
- **String**: several medium power inverters (e.g. 6 × 50 kW)

String modularity is preferred for flexibility and resilience (Table 4).

Table 4: Detailed comparison

Criteria	Centralized	String (6 × 50 kW)
System performance	+1 point (optimized DC/AC conversion)	+0.5% (Multi-string MPPT)
Maintenance	Simple (1 piece of equipment only)	Modular (targeted intervention)
Redundancy	Null (failure = total shutdown)	Fault tolerance (partial production maintained)
DC wiring cost	Low (direct field connection)	Higher (cable multiplication)
Shade adaptation	Low (Global MPPT)	Excellent (MPPT per string)
Flexibility	Weak (frozen architecture)	Strong (easy addition or removal of inverters)
Security	High risk in case of breakdown	Limited risk, rapid intervention
Facility	Compact but centralized	Distributed, better thermal management

8. ELECTRICAL SIZING

8.1 Series/Parallel Modules

Sizing the photovoltaic modules is the first essential step in designing a solar power plant. To achieve a peak power of 300 kWp, 350 Wp monocrystalline modules were chosen. The total number of panels required is therefore obtained by dividing the total power by the unit power:

- Total: 300,000 Wc ÷ 350 Wc≃858 panels
- By inverter: 858 ÷ 6≃143 panels
- Strings: 2 × 72 panels (Umpp × 72 = 2765 V > Umin_inv = 800 V)

To optimize energy conversion and management, these panels are distributed across six SMA STP 50-40 inverters. Each inverter supports approximately 143 panels. The configuration adopted is two strings of 72 modules connected in series per inverter. This arrangement allows for an operating voltage of:

- Ustring =72×38.4 V = 2764.8 V

This voltage is significantly higher than the inverter's minimum input voltage (800 V), ensuring operation within the optimal Maximum Power Point (MPP) range.

8.2 Wiring

Cabling plays a critical role in the transmission of the energy produced, and its sizing must comply with electrical safety standards while minimizing Joule effect losses.

a. Direct current (DC) side

The connection between the modules and the inverters requires approximately 1,000 meters of 10 mm^2 copper cable. Taking into account the resistivity of copper ($\rho = 0.0175\ \Omega \cdot mm^2/m$), the voltage drop can be estimated using the formula:

$$\Delta U = \rho \cdot L \cdot I / S$$

With :

- L=1000 mL
- I=20 A (average current per string)
- S=10 mm^2

This represents a voltage drop of only 1.75% on a voltage of 2000 V, well below the recommended maximum threshold of 3%.

b. Alternating Current (AC) Side

The inverters' output to the grid requires 300 meters of 50 mm^2 copper cable. The nominal current is 125 A, and the associated circuit breaker is rated at 160 A to ensure adequate protection against overloads.

8.3 Estimated Total Losses

In any photovoltaic installation, several factors contribute to the reduction of energy yield. These losses must be quantified to assess the system's Performance Ratio (PR). Here is an estimate of the main sources of losses (Table 5):

Table 5: Estimation of the main sources of losses

Source	**Losses (%)**
Shadows and Mismatch	4.8
Temperature	9.5
DC & AC Cables	2.8
Inverter	1.8
Soiling	3.5
Estimated total	**22.4%**

Mismatch losses arise from performance differences between modules, while thermal losses are due to temperature rise, which reduces cell efficiency. Cable losses are related to ohmic resistance, and inverter losses are related to its conversion efficiency. Finally, module contamination by dust or pollutants reduces the amount of captured radiation.

9. DYNAMIC SIMULATION UNDER PVSYST

The dynamic simulation carried out using the PVsyst software makes it possible to accurately assess the

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E-ISSN: 2582-2160 ● Website: www.ijfmr.com ● Email: editor@ijfmr.com

energy performance of a photovoltaic system over a full year, taking into account the technical, climatic and geometric parameters of the project.[10, 11].

9.1 Simulation Setup

The simulation setup was performed according to the following criteria:

- Climate: The climate file used is a TMY (Typical Meteorological Year), ensuring a reliable representation of average weather conditions at the installation site. The inclined global irradiation forms the basis of the calculation, taking into account the tilt angle of the panels.
- Photovoltaic modules**:**The selected panels are of the SW 350 type, incorporating the single-diode model for realistic modeling of the electrical behavior of the cells. This model allows recombination effects and internal losses to be simulated with good accuracy.
- Inverters : The system is equipped with SMA STP 50 inverters, whose efficiency is expressed according to an efficiency curve that varies depending on the load. This allows for a reliable estimation of direct current/alternating current conversion losses.
- Panel layouts**:**The installation consists of six south-facing rows (slopes), inclined at 25°, with a spacing of 4.5 meters between each row. This design aims to minimize mutual shading while optimizing solar capture across the entire surface.
- Climate: TMY file, tilted global irradiation.
- Modules: SW 350, param. single-diode.
- Inverters: SMA STP 50, efficiency curve.
- Layouts: 6 south-facing slopes, 25° inclination, 4.5 m spacing.

9.2 Simulation Results

The dynamic simulation allowed to obtain the following performances:

- **Estimated annual production**: 485 MWh of energy produced over the year, which reflects efficient exploitation of available solar resources.
- **Performance Factor (PR)**: 77.2%, reflecting the ratio between the energy actually produced and the energy theoretically available. This level indicates a well-optimized system, with limited losses.
- **Yield Ratio (YR)**: 1,545 kWh/kWp, representing the amount of energy produced per kWp installed, on an annual basis. This yield is considered very satisfactory for installations in a Mediterranean climate.
- **System availability**: 98.4%, highlighting the reliability of the installation and the consistency of its production, with a near-zero breakdown or unavailability rate.

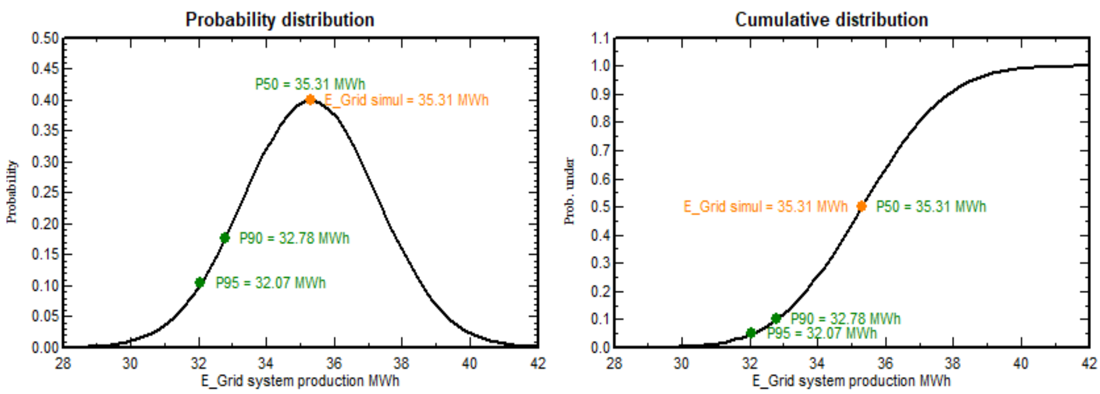

Figure 2: Analysis of energy losses of a photovoltaic system under PVsyst

10. RELIABILITY AND MAINTENANCE

The reliability of a photovoltaic system directly determines its long-term performance and the project's profitability. An optimized maintenance strategy, based on clear indicators and effective monitoring protocols, helps minimize production downtime and guarantee high availability.

10.1 KPI performance indicators

In order to assess the operational efficiency of the system, three key indicators are used:

- MTTR (Mean Time To Repair): The average time to repair critical components, including inverters, is estimated at 2 hours, thanks to reactive corrective maintenance and the availability of spare parts.
- MTBF (Mean Time Between Failures): The reliability of the equipment is illustrated by an MTBF of 15,000 hours, or more than 20 months of continuous operation before failure.
- Availability: The system availability rate is maintained above 98%, notably thanks to string redundancy, allowing the system to continue operating even in the event of partial failure.

These indicators guarantee continuity of service and limitation of energy losses linked to technical shutdowns.

10.2 Maintenance strategies

Several strategies have been implemented to anticipate breakdowns, optimize performance and extend the life of the installation:

- SCADA (Supervisory Control and Data Acquisition): The SCADA system provides real-time monitoring of operating parameters, with automated alarm generation, particularly in the event of MPPT drift. This allows for proactive intervention before production is affected.
- Module cleaning: A quarterly cleaning cycle is applied to limit losses due to fouling. According to Kyocera et al. (2019), this practice improves the Performance Ratio (PR) by +2.3%, which represents a significant energy gain on an annual scale.

By combining these advanced monitoring methods and regular field actions, the photovoltaic plant ensures reliable and sustainable operation.

11. DETAILED ECONOMIC ANALYSIS

The economic evaluation of a photovoltaic power plant is a crucial step in investment decision-making. It not only allows for the estimation of the project's profitability, but also for the analysis of cost distribution and the impact of financial support. This section details the components of CAPEX, key economic indicators, and the long-term financial viability of the project.

11.1 Decomposition of CAPEX

The following table shows the breakdown of investment costs (CAPEX) by item for a 300 kWp power plant, expressed in €/kWp and as a percentage of the total cost:

Post Office Post Office	**Amount (€/kWc)**	**% of CAPEX**
Photovoltaic modules	0.30	40%
Inverters (6 × 50 kW)Inverters (6 × 50 kW)Inverters (6 × 50 kW)	0.07	10%
Civil engineering & assembly	0.25	33%
Cables & protections	0.10	13%
Studies & connection	0.05	4%
Total	**0.77 €/kWc**	**100%**

The total cost of the installation is estimated at €231,000, including the supply of equipment, on-site implementation and administrative procedures.

11.2 Profitability indicators

In order to assess the financial performance of the project, several economic indicators are analyzed:

- LCOE (Levelized Cost of Electricity): The levelized cost of electricity is estimated at €0.065/kWh, according to the standards established by Fraunhofer ISE (2021). This cost is significantly lower than the average feed-in tariff offered by STEG (€0.12/kWh), which guarantees a comfortable profit margin.
- IRR (Return on Investment): Thanks to high energy performance and low OPEX (€3,000/year, including insurance and maintenance), the return on investment is achieved in 6.2 years, including a 30% subsidy on CAPEX.
- NPV (Net Present Value)**:**Considering an 8% discount over 25 years, the net value of the project reaches +€120,000, illustrating robust long-term profitability.

11.3 Comment on the assumptions

- The annual production of 485 MWh is realistic for a well-oriented, shade-free 300 kWp power plant.
- Public subsidies play a key role in reducing the return on investment time.
- Low OPEX is made possible by system reliability, string redundancy and an optimized maintenance strategy.

12. ENVIRONMENTAL IMPACT

Assessing the environmental impact of a photovoltaic installation is not limited to renewable energy production alone. It also includes the avoided carbon footprint, the life cycle analysis (LCA) of components, and energy return indicators. This comprehensive approach makes it possible to quantify the short- and long-term ecological benefits of the project.

12.1 Avoidance of CO_2 emissions

Producing electricity from photovoltaic panels significantly reduces greenhouse gas emissions by replacing part of conventional fossil fuel-based generation. In Tunisia, the emission factor of STEG's electricity mix is estimated at 0.5 $kgCO_2$ per kWh produced.

Thus, for an annual production of 485,000 kWh, the photovoltaic installation makes it possible to avoid:

- STEG emission factor: 0.5 $kgCO_2/kWh$
- CO_2 avoided: 485,000 kWh × 0.5 = 242.5 tCO_2/year
- Over 25 years: 6,062 tCO_2 avoided

This figure corresponds to the equivalent of more than 20 million kilometers traveled in a thermal vehicle, or the replanting of more than 75,000 trees over the period.

12.2 Life Cycle Assessment (LCA)

For a rigorously scientific approach, the evaluation of the ecological balance sheet must also integrate the Life Cycle Analysis (LCA) of the equipment, according to a so-called “cradle-to-grave” approach, encompassing:

- Manufacturing of modules and inverters
- Transport and installation Transport and installation Transport and installation
- Exploitation Exploitation
- End-of-life decommissioning

According to data reported by Saidani & Moussi (2024), the gray energy – i.e., the energy required to manufacture the modules and inverters – is offset in less than 1.5 years thanks to the renewable production of the installation. This means that the system becomes "neutral" from an energy point of view very quickly after its commissioning.

Another key indicator of environmental sustainability is EROI (Energy Return On Investment), which refers to the ratio between the energy produced by the system over its lifetime and the energy invested to build it:

EROI = Energy produced over 25 years / Gray energy ≈ 25

This result is in the high range of photovoltaic installations, indicating excellent environmental performance and robust energy efficiency.

13. GENERAL CONCLUSION

This study confirms the technical feasibility and economic viability of a 300 kWp photovoltaic power plant integrated into a residential roof in Tunisia, aligning with STEG requirements and international standards. The adoption of a string architecture, combined with optimized sizing, rigorous PVSyst modeling, and an in-depth life cycle analysis (LCA), allows for the design of a project that is robust, efficient, and sustainable.

The system achieves a Performance Ratio (PR) of 77%, demonstrating good energy conversion in real-life conditions, while its Levelized Cost of Energy (LCOE) of €0.065/kWh and its Payback Time (IRR) of only 6 years illustrate its medium-term economic viability.

With a view to sustainable development and energy transition, several areas for improvement and expansion are envisaged:

- The integration of stationary storage systems and smart residential demand management solutions to optimize self-consumption and improve grid resilience.
- Regional cooperation in the MENA region, particularly around cross-border projects such as DESERTEC, aimed at harnessing the desert's solar potential to create large-scale mega photovoltaic power plants and promote energy interconnection.

Thus, beyond its local benefits, this project is part of a regional and global dynamic of decarbonization, energy resilience, and climate justice, paving the way for reproducible models with high added value for the territory.

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