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Utility Scale Ground Mounted Photovoltaic Plants with Gable Structure and Inverter Oversizing for Land-Use Optimization

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Abstract: The paper proposes an effective layout for ground-mounted photovoltaic systems with a gable structure and inverter oversizing, which allows an optimized use of the land and, at the same time, guarantees a valuable return on investment. A case study is presented to show the technical, economic, and environmental advantages compared with conventional "fixed-tilt" and "sun-tracking" ground-mounted photovoltaic installations. The main advantage of this solution is that it maximizes the energy produced per unit of land area used; but, also considering the economic metrics, the net present value of the proposed PV arrangement solution results in a greater annual volume of energy produced and therefore of net revenues and cash flows, and greater than the compared conventional solution with modules exposed in an optimal fixed position or which make use of sun-tracking systems.

Keywords: solar photovoltaics; ground mounted photovoltaic; sun tracking systems; optimization; photovoltaic array configurations; land use; ecological footprint; inverter sizing; renewable energy

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1. Introduction

The recent approval of the measures contained in the Clean Energy for All European Package defined the framework within which the Member States of the European Union must move to pursue the objectives of decarbonization established by the Paris Agreement for the next years, through the development of renewable production plants, which must to be sustainable and have minor impact on the environment as well as on land consumption. The coming period from 2021 to 2030 foresees the achievement of several EU-wide milestones and policy objectives defined by the 2030 climate and energy framework and the European Green Deal which includes an action plan aimed at, among other objectives, to invest in environmentally friendly technologies, decarbonize the energy sector and ensure the greater energy efficiency of buildings. In the EU, there is a binding target for renewable energies for 2030 which will have to meet at least 32% of final energy consumption, including the revision clause by 2023 for an upward revision of the target at the EU level [1]. According to this framework, the promotion of the development of renewable sources as an essential element for decarbonization requires a big effort for each State in defining appropriate policies for the development of renewable production plants, which must be sustainable and with minor impact on the environment as well as on the land consumption. Member States are obliged to adopt integrated National Climate and Energy Plans (NECPs) for the period 2021–2030, and in Italy, for instance, the NECP envisages that the contribution of renewables to the total gross final consumption to 2030 (30%) will be differentiated between the different sectors: 55.4% of renewable share in the electricity sector, 33% renewable share in the thermal sector (uses for heating and cooling), and 21.6% concerning the incorporation of renewables in transportation [2]. In particular, the forecasted increase in the share of consumption covered by renewable sources, equal to 30% at 2030, has been defined considering, in the electricity sector, the intermittent nature of the sources with greater development potential, mostly wind and photovoltaic (PV), and, in the thermal sectors, the limits to the use of biomass, consequent to the contextual air quality objectives, as well as the need to contain land consumption [2]. The last one is a very demanding objective, which will entail, in the electricity sector, the upgrading of the power system infrastructure, able to cope with the widespread diffusion of wind and PV, with an expected average annual installed capacity of more 3000 MW/year from now to 2030. This spreading of wind and PV will also require the massive adoption of distributed and centralized energy storage systems, both for the security needs of the system, and to avoid having to stop renewable plants and curtail energy production in periods of low electricity demand. In addition, important efforts will also be required to increase the consumption of renewable energy for heating and cooling, particularly in terms of the diffusion of heat pumps, and for electric transportation [3], particularly in urban contexts [4].

A similar scenario is expected globally, and the IEA found that PV generation globally increased 31% in 2018 and represented the largest absolute generation growth (+136 TWh) of all renewable technologies. In the IEA sustainable development scenario (SDS) 2000–2030 for solar PV power generation, PV is still on track to reach projected levels despite recent political changes and uncertainties in China, India and the United States, which will require an average annual growth of 16% between 2018 and 2030 (Figure 1) [5].

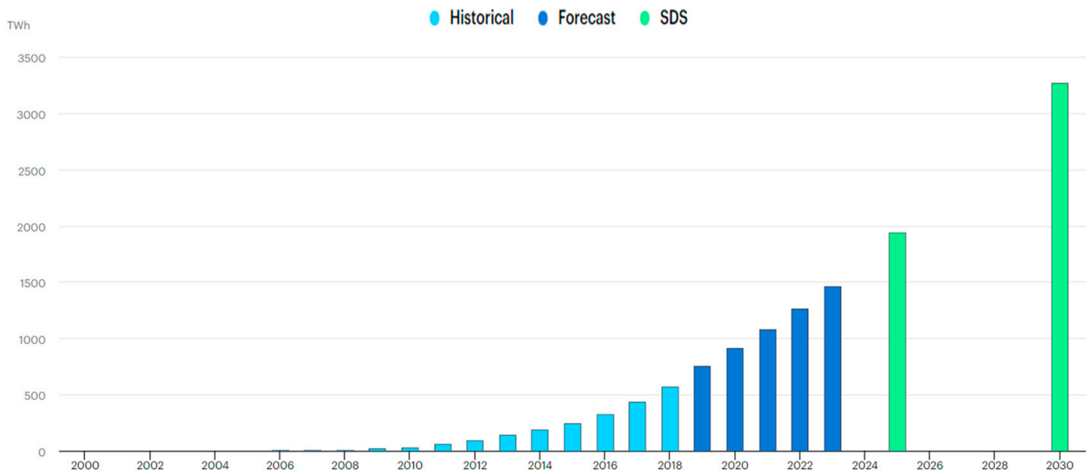


Figure 1. IEA SDS 2000–2030 for solar PV power generation. Source [5].

Thanks to the increased cost competitiveness and worldwide widespread political support, solar PV is expected to grow robustly over the next five years, led by China, the United States, India and Japan. Growth should also accelerate in Latin America, the Middle East and Africa thanks to greater economic attractiveness and political support from national governments [5–7]. According to this scenario it is then predicted that solar photovoltaic systems will have a tumultuous development that will see the value of the current installed capacity to became triple or more.

In solar energy harvesting applications, soil occupation, energy collection and conversion efficiency, reversibility to the unperturbed state are factors inextricably intertwined. All these aspects are worthy of a deep investigation if the repercussions on the land-use need to be established [8]. Utility-scale solar energy development, including impacts on biodiversity, land-use and land-cover change [9], soils, water resources, and human health, need to be deeply and correctly evaluated—in particular the layout—as the infrastructural and architectural design of a solar power plant may impact the ecosystem recovery or reversibility [10]. Up to 31 impacts related to issues of land use, human health and well-being, wildlife and habitat, geohydrological resources, and climate were identified and appraised in [11].

The purpose of this paper is therefore to propose new installation solutions for the construction of utility scale PV systems, maximizing production per unit of land, in a context of guaranteed economic advantage, considering the current price of energy in the markets and accordingly to the concept of grid parity.

This paper is organized as follows. Section 2 describes the typical installation design techniques "fixed-tilt" and "sun-tracking" for ground mounted photovoltaic plants. Section 3 introduces the proposed gable structure installation and inverter oversizing for land use optimization in solar PV production. Section 4 introduces the techno-economic factors that are used to evaluate the profitability for solar PV plants. Section 5 presents the comparison among the optimized gable structure and the conventional fixed tilt/tracking arrangements. Finally, Section 6 presents the conclusions of the study.

2. Conventional Design Techniques for Ground Mounted Photovoltaic Plants

In this section the typical ground mounted PV installation structures adopted are summarized.

Common structures adopted for solar photovoltaic (PV) power plants utilize three main types of racking systems:

- Fixed-tilt;
- Single-axis tracker;
- Dual-axis tracker.

2.1. Fixed PV Systems

Fixed systems remain in the same orientation at all times, while trackers tilt and rotate to orient the solar panels, capturing the most amount of energy every day and all seasons. The solar tracking systems automatically adjust the positions of the photovoltaic modules so that they constantly "track" the sun during the day [12,13]. Depending on the exact location and details, solar panels on trackers will produce significantly more electricity than fixed solar panels [14,15].

The performance of the photovoltaic system changes depending on the orientation (azimuth) and inclination (tilt) of the photovoltaic modules. The "inclination" is the angle of the modules with respect to the horizontal plane (of the ground) and the orientation is related to the relative position respect to the cardinal points: north, south, east, west.

In a fixed-tilt system the positions of the modules are always at a fixed tilt (Figure 2a) and orientation (Figure 2b).

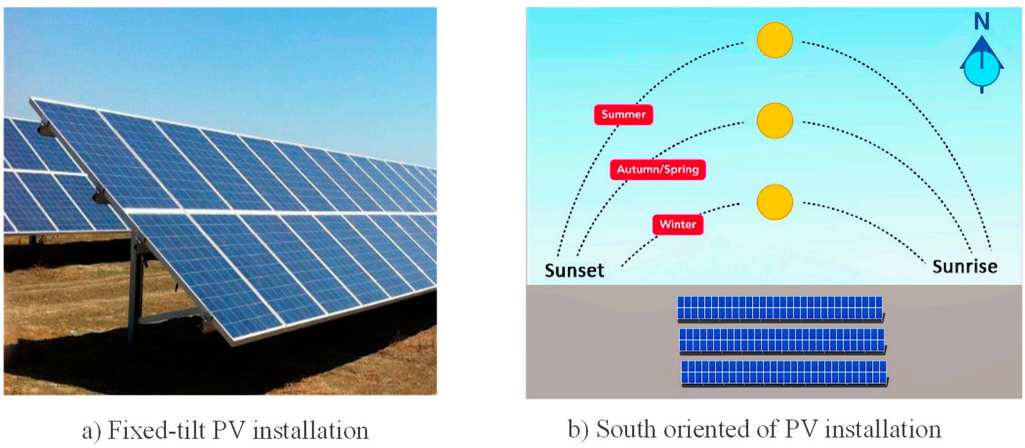


Figure 2. Fixed-tilt installation PV systems.

The optimal inclination of the photovoltaic panels changes at each latitude while the optimal orientation is south (0° S) for the northern hemisphere and north (180° N) for the Southern Hemisphere.

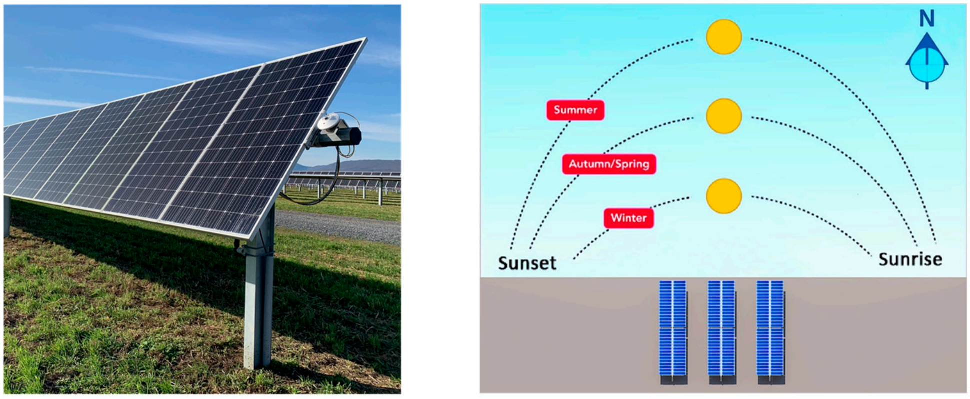
2.2. Sun Traking PV Systems

Solar trackers are devices capable of directing photovoltaic modules towards the sun, also using reflectors, lenses or other special optical devices to convert solar energy [12,13].

In flat-panel PV applications, trackers are used to minimize the angle of incidence between the incoming light from the sun and a PV panel, which increases the amount of energy produced from a defined installed power generating capacity.

Generally speaking, single axis trackers can improve the energy production typically by 25%, whereas a correctly installed dual-axis trackers can increase up to about 40% [15,16].

At present, single-axis trackers are the most common tracking systems installed worldwide (Figure 3). In fact, although dual-axis trackers can increase total energy production by 5–10% above a single-axis tracker, single-axis trackers are more cost-effective and reliable. The additional energy produced by a dual-axis tracker rarely, if ever, outweighs the additional land, installation and operations and maintenance (O/M) costs required.



a) Single-tracker PV installation b) East-West orientation of PV installation

Figure 3. Single tracker PV systems.

2.3. Fixed and Sun-Tracking Comparison and Critical Mounting Issues

2.3.1. Energy Harvesting

One- or two-axis tracking systems increase energy production by 15–30% compared to a fixed-tilt photovoltaic array of the same size.

One or two axis trackers are able to provide additional energy production resulting in increased project revenues. In order to understand if these additional revenues will support the higher costs of a solar tracking system, a careful evaluation of the technical and financial characteristics of the project is always necessary.

2.3.2. O/M Comparison

Tracking systems require higher maintenance costs for the 25-year life of the photovoltaic system. Such systems include motors, sensors and moving parts that fixed tilt systems do not have, and which require additional maintenance costs. In particular, it is common and correct to estimate up to 10–15% more O/M costs for PV systems that use solar tracking devices [17].

2.3.3. Critical Mounting Issues and Land-Use

Sun tracking systems are not always technically or economically viable, and it depends on several technical issues such as site topography, soil conditions mainly, wind loads, and so on. For instance, the site topography is binding on the viability and profitability of solar tracking systems because the trackers must be installed in relatively flat locations [18].

Critical mounting issues can occur also for the PV projects that are being developed on less-than-ideal sites—those with undulating terrain, irregular boundaries or obstacles—or unfavorable and variable geotechnical conditions such as steep slopes, gradients or other irregularities or unfavorable/critical conditions such as rocky agricultural land, or land where former quarries or former landfills exist, or non-flat industrial land that is difficult to use. If a site happens to have one or more of these challenging conditions, then a fixed-tilt solution, or a hybrid of tracker and fixed-tilt, might be the most advantageous way to follow.

Each tracker segment is typically 75–100 m (75–100 PV modules) in length and cannot be installed at grades exceeding 5–6%.

In addition, the roughness of the ground must be reduced within the tracker segment by leveling the ground within a certain tolerance. With these restrictions, sites with sloping or non-flat terrain will require extensive leveling and additional costs that typically make trackers uneconomical. Finally, due to the correct sizing to avoid shading phenomena, the tracker systems also have larger footprints per MW than the fixed inclination systems. The impact of the cost of the additional land must be taken into account in the economic and financial plan of the project as well as for the environmental impact in terms of land occupation.

3. Gable Structure and Inverter Oversizing for Optimized Land Use PV Installation

3.1. The Gable Structure for PV Racking

The structure proposed by the authors in this paper, and schematically depicted in Figure 4, is designed regarding the trend of the rapid decline in the prices of photovoltaic modules that has led investors to prefer increasing the power of PV systems to achieve energy goals rather than using more complex tracking systems that improve the specific production per kWp installed, with the further consideration linked to the fact that reaching the sustainability objectives of increasing renewable energy penetration among total energy usage requires limiting of the use of land.

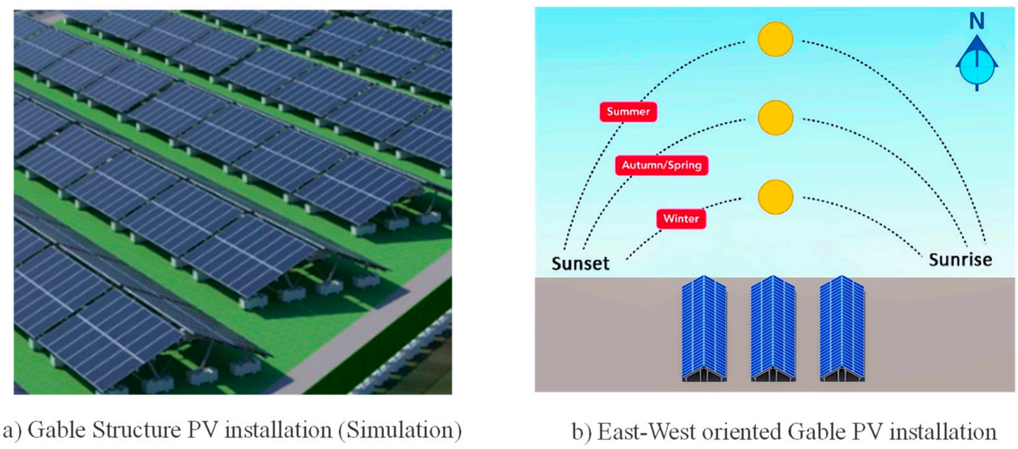


Figure 4. Gable structure for PV systems.

The gable structure for grounding mounted PV systems is illustrated in detail in Figure 5. Figure 5 shows the section of the structural configuration that is based on concrete blocks, but other types of anchors are also possible, for example those obtained by driving into the ground. The overall three-dimensional structure of a whole array is shown in Figure 6.

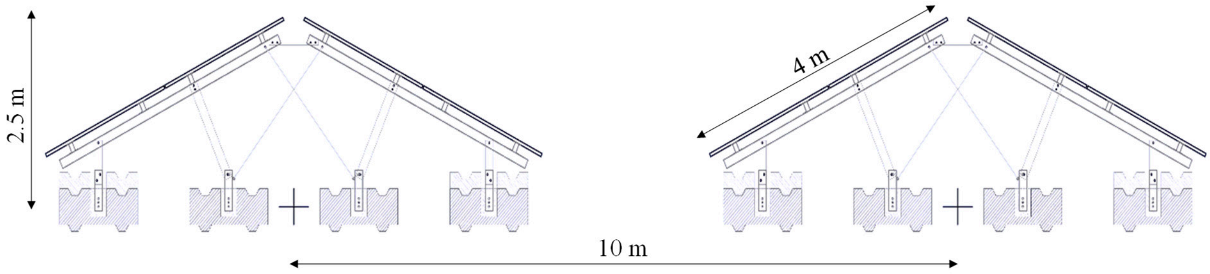


Figure 5. Gable structure for PV systems: main dimensions.

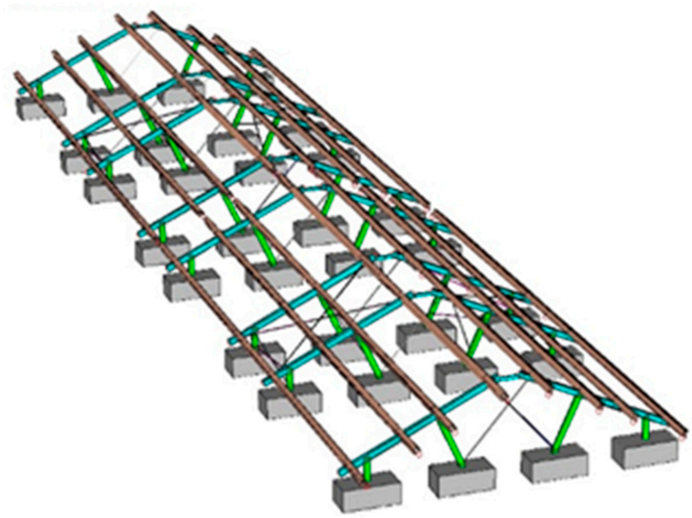


Figure 6. Gable structure for PV systems: structural model.

The proposed structure has the following characteristics:

1. Fixed positioning of the modules with a gable configuration having 50% of the fixed modules oriented to east (azimuth −90°) and 50% of the fixed modules oriented to west (azimuth 90°); the identification of the inclination angle of the modules (tilt) is not defined and may vary in relation to the assessments to be made for each individual project based on the site of location (Tilt $\simeq 25\ ^{\circ}$) and other applications, for instance for floating PV systems.
2. Parallel coupling to the same inverter (same MPPT), of the strings of the modules oriented both east/west.
3. Oversizing of the inverter; coupling between photovoltaic modules and inverters with a ratio between the power of the DC PV generator (sum of the nominal powers of the modules connected to the inverter) and the nominal power of the inverter (indicative values of the ratio may reach 1.5–1.8).

The gable structure presents several benefits, even if compared with the fixed tilt and sun tracking ones, in particular the following aspects can be underlined:

- Static and robust mechanical support solution for modules; lower risks in the event of exceptional winds and other extreme weather events;
- Mechanical suitable on slopes and terrain undulating;
- Absence of failures resulting from moving parts;
- Absence of electrical cables for auxiliary power supply/tracker control systems;
- Shorter cable length, due to the halved extension of the system, resulting in a proportional reduction in the risk of cable failure;
- Reduction in the length of power cables (parallel strings in DC and cables in AC) around 35%;

- Reduction of the extension of underground cables and consequent ease of troubleshooting on cables;
- Limitation of Joule losses in power cables with the same section required for compliance with the thermal limit;
- Unavailability due to faults mainly attributable to the inverters alone;
- Extremely easy and quick cleaning of the modules equally arranged on the right and left of the aisle;
- Ease and speed in finding and repairing faults.

3.2. Inverter Oversizing

The PV inverters are sized according to the maximum output power, which will be defined according to the maximum rated power, the AC output voltage and the maximum current in the circuits.

In PV installations, oversizing the inverter, i.e., having more DC power than the inverter AC power, is used to increase the output power in low insolation conditions, thus allowing the installation of a smaller inverter for a given DC array or, alternatively, the connection of a larger DC photovoltaic generator for a defined inverter. With the oversizing of the inverter higher energy yields can be generated and it is possible to increase the profitability of the PV power plant [19]. However, excessive oversizing of the inverter may have a negative impact on the total energy produced and on the inverter lifetime [20].

The size of the inverter can be larger or smaller than the DC rating of the solar PV array, to a certain extent. The array-to-inverter ratio DC/AC of a solar PV system is the DC rating of the PV modules (i.e., rating of the DC generator) divided by the maximum AC output of the inverter.

DC/AC oversizing is defined as the ratio between the nominal power $P_{DC(STC)}$ of the PV array at standard conditions STC (radiation of 1 kW/m^2, a cell temperature of 25 °C) the maximum output (rated/nominal power of the inverter) of the inverter in AC $P_{AC,MAX}$ (1)

$$\frac{DC}{AC} oversizing\% = \frac{P_{DC(STC)}}{P_{AC,MAX}} \cdot 100 \quad (1)$$

One of the main reasons to oversize the DC generator is that the theoretical peak power of the modules is often not achieved in reality. Thus, a certain minimum of oversizing is necessary to compensate for losses.

Reasons for this include [19–22]:

- Irradiation values are not achieved (e.g., in the winter months);
- Ambient temperatures are too high;
- Pollution of the modules;
- Suboptimal orientation of the modules throughout the day (the factor decreases significantly with tracking systems);
- Reduction in module performance over time due to natural aging: module performance drops annually by approximately 0.5%; after 25 years approximately 80% of the original nominal power still remains;
- Mismatching losses;
- Voltage drop in the string cables, which moves the actual working point from the ideal point of maximum power, between strings near and far from the inverter;
- Joule effect losses in the DC string cables up to the inverter;
- Joule effect losses in blocking diodes (where installed).

The majority of installations will have a DC/AC ratio between 1.15 to 1.25; inverter manufacturers and solar system designers typically do not recommend a DC/AC ratio higher than 1.55. Oversizing the PV array is not recommended, because it can cause clipping when the PV solar panels are producing excessive DC power for the inverter (Figure 7) [19–22]. When this happens, anyway the inverter will limit the amount of energy that it is converting to the maximum power in AC, then resulting in power losses.

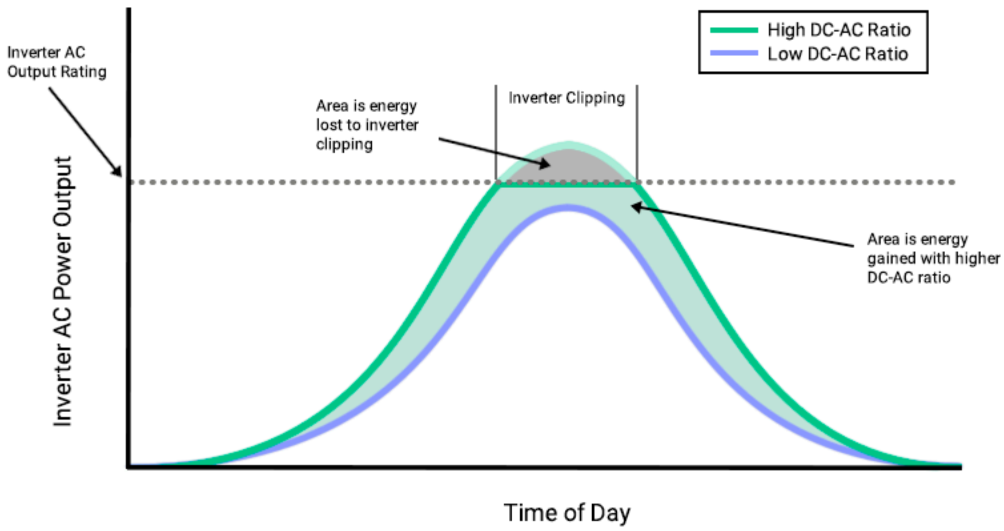


Figure 7. Clipping in PV systems due to high DC/AC ratio. Source: www.aurorasolar.com accessed on 26 May 2021.

On the other hand, it is not advisable to install a solar inverter much larger than the PV modules ($\frac{DC}{AC} < 1$) because the inverter will work not efficiently.

The main reason to oversize an inverter is to drive it to its full capacity more often. This will maximize power output in low light conditions, thus allowing the installation of a smaller inverter for a given DC array (or alternately installation of more DC power for a given inverter). Oversizing the inverter is typically not a requirement, however an experienced PV designer may choose to oversize the inverter in order to maximize the power production, due to actual PV module power vs. module nominal power and financial considerations. In fact, due to further declining module prices, driven by factors, including by supply and demand, as well as the continuous improvement of the technology—and thus the possibility of using more modules per inverter—higher oversizing becomes more and more economical.

On the other side, oversizing the inverter may cause the inverter to operate at high power for longer periods, thus affecting its lifetime. Operating at higher power also increases inverter heating, even if inverter will reduce its peak power generation in case of overheating, and may heat its surroundings [19,20].

For the proposed configuration, the total irradiation on the photovoltaic modules derives from the sum of the irradiations (half and half) on each side of the structure (Figure 8) for the month of July.

The solar energy that is actually available to the inverter, considering the losses due to overtemperature (and other) in the modules, assuming 16% BOS efficiency is showed in Figure 8 and the energy actually converted in Figure 9.

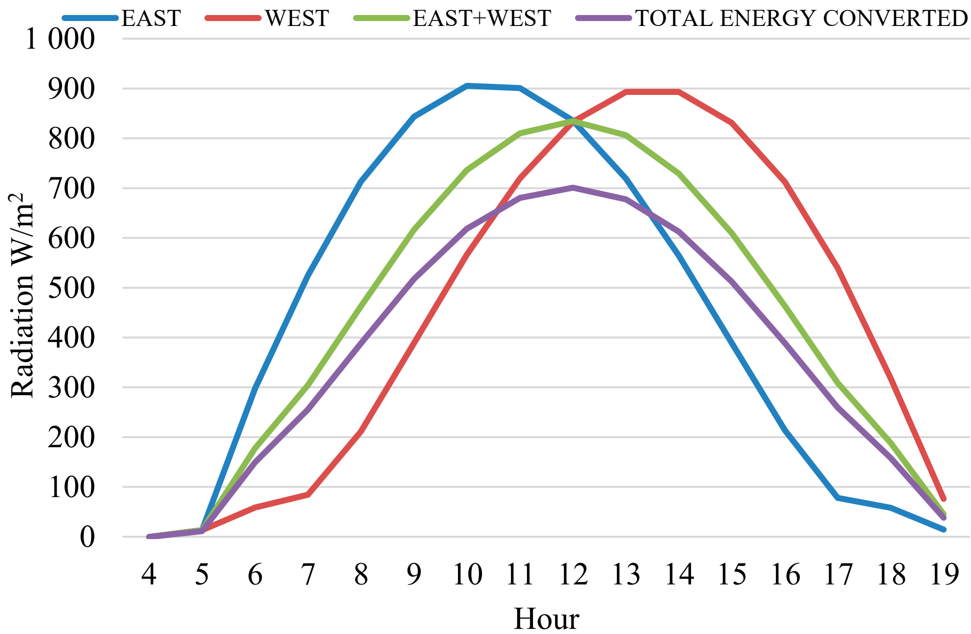


Figure 8. Irradiation combination applied to the inverter (month of July).

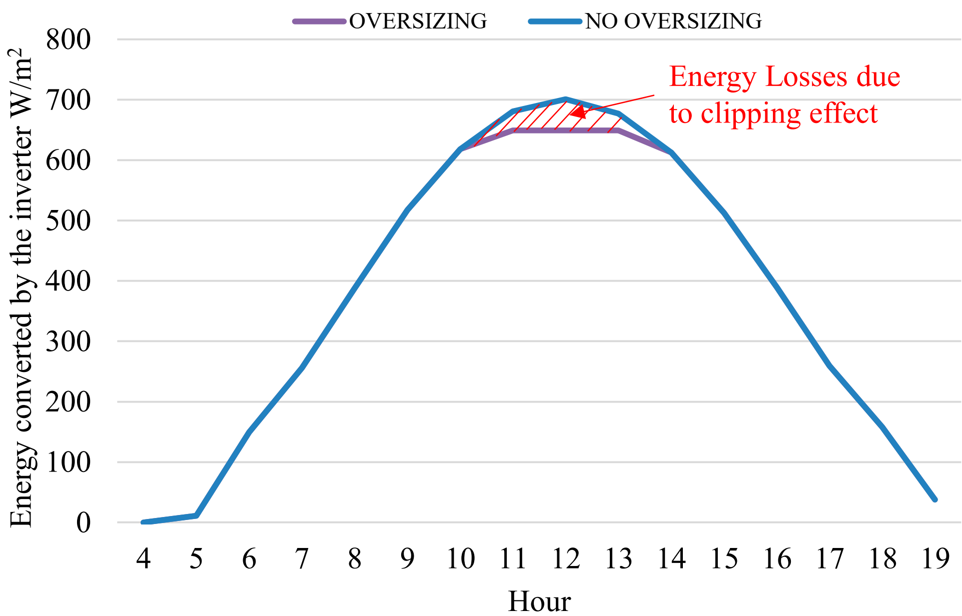


Figure 9. Energy converted by the oversized inverter and "clipping" losses for July month.

The energy not exploited, since the corresponding DC power values are greater than the inverter rated power, increases with the oversizing ratio (1) [21]. The value of the inverter oversizing chosen in the paper, equal to 1.55, comes from the choice of authors of limiting the inverter losses due to clipping below 1% (Figure 10).

Considering the oversizing ratio of 1.55, the annual energy lost is approximately 0.67%; if the oversizing ratio would be higher this contribution of energy lost due to the clipping effect would increases accordingly.

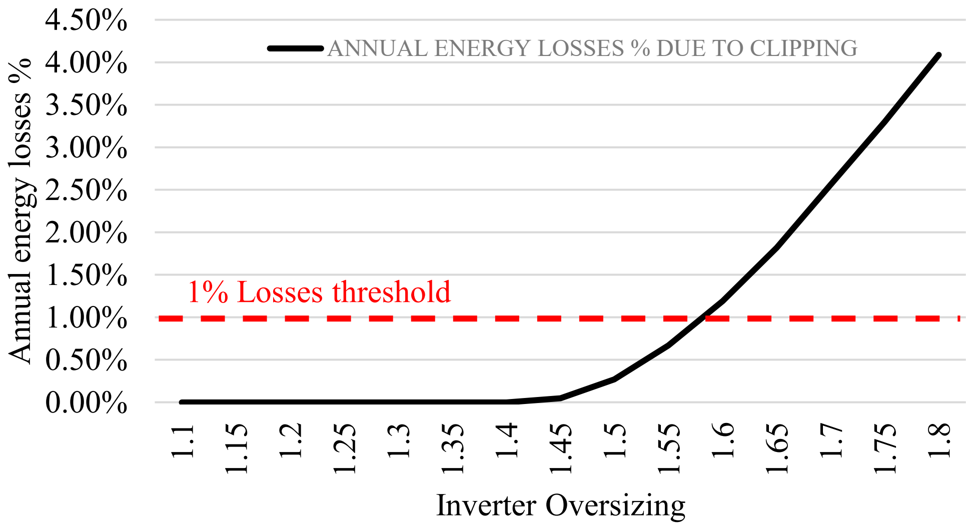


Figure 10. Annual energy "clipping" losses in % due to inverter oversizing.

4. Financial and Profitability Evaluation Techniques for Photovoltaic Installations

This section describes the common tecniques used for assessing the potential financial performance of a photovoltaic installation [23–25]. In particular, the parameters usually taken into account for technical and economic evaluation of PV installation and, in general, for energy production facilities [25], are the following:

- Site location (latitude);
- Orientation and inclination of solar photovoltaic generator;
- Guaranteed return of photovoltaic solar generator;
- Indexing in tariff of electric kWh produced;
- Fiscal situation of the owner (net of tax credits);
- Incentives and grants;
- Products suitable financing.

4.1. Net Present Value

In PV power plant design and optimization, the main economic parameter frequently considered to identify the most cost-effective solution is the net present value (NPV), defined as the sum of the discounted cash flows calculated over the system lifetime. During the initial development stages of the PV project, the multiple design solutions analyzed in the paper have a varying CAPEX (capital expenditure) and OPEX (operating expenditure) scenarios; for this reason apart from comparing the various technical options, there is a need to also select most advantageous solution [24].

This may not necessarily be a client requirement, but in my view should be analyzed to help the decision makers choose the optimum cost solution and the NPV of the various options will need to be calculated and compared.

Cash flows (CF) are obtained from the difference between the annual revenues and costs and of the system, which are discounted to the present by the use of an interest rate. NPV is evaluated with (2):

$$NPV(i, N) = \sum_{k=1}^{N} \frac{(R_{K,TOT} - C_{K,TOT})}{(1+i)^N} \quad (2)$$

where:

- $R_{K,TOT}$ = total annual revenues of the system (Euro/y);
- $C_{K,TOT}$ = total annualized cost of the system including CAPEX and OPEX (represented by the sum of the costs for each system component) (Euro/y);
- i = interest rate (%) or discount factor;

- N = project lifetime (y).

The NPV of a component is the present value of all the installation and operation costs of the project and takes into account of the costs and the revenues over the project lifetime. The capital cost occurs at the start of the project. The annual operation and maintenance (O/M) and fuel costs occur at the end of each year. The replacement costs occur every defined number of years. This equation discounts each year's cash flow back to the present, then deducts the initial investment, which gives a net value of the investment in today's Euros. The discount factor is the key input for the NPV calculation, which indicates the project's risk and investors return expectations on the investment. The cost of capital for an investor is the minimum rate that it must earn from investment projects in order to satisfy the required rates of its suppliers of finance, so it is used as the discount factor when calculating an NPV. In general, when evaluating different investment alternatives, a positive NPV during the service lifetime indicates that the investment has a positive effectiveness.

4.2. Internal Rate of Return

The internal rate of return (IRR) expresses the time value of the annual savings of the equipment investment so that it is comparable to the interest rate one might earn by investing cash in a bank account or in securities. It is a discount rate, the one that makes the present value of the future cash flows equal to the cost of the investment [24].

4.3. Discounted Payback Time

The discounted payback time (DPT) measure indicates the number of years required to recover the initial investment and represents an alternative means of evaluating the cost-benefit of a project. It is well known that a more effective investment is represented by a smaller DPT value. Basically, the DPT represents the smallest value of variable k so that the value of the NPC in (2) is equal to zero [24].

4.4. Levelized Cost of Electricity

The levelized cost of electricity (LCOE) is another economic parameter commonly used to compare alternative power generating technologies that represents the average cost for a kWh of energy produced by a PV system. It is calculated for a reference year by dividing the cumulative system costs by the total amount of energy produced during the same time period.

The Levelized Cost of Energy (LCOE) is evaluated as the average cost per kWh of electrical energy produced by the system. The LCOE is evaluated as the rate by the annualized cost of producing electricity and the total electric energy production as in (3):

$$LCOE = \frac{C_{Y,TOT}}{E_L + E_{G,S}} \quad (3)$$

where:

- $C_{Y,TOT}$ = total annualized cost of the PV system (Euro/y);
- E_L = load energy served (kWh/y);
- $E_{G,S}$ = grid energy sales (kWh/y).

5. Case Study, Comparison and Discussion

The proposed structure for PV modules with inverter oversizing is compared with the two main installation solutions currently adopted for utility scale photovoltaic systems (conventional solutions) with the following assumptions:

- Shed structure with fixed modules oriented to the south (Azimuth 0° S), with optimal inclination (tilt 30°) in relation to latitude.
- The monoaxial trackers are assumed with horizontal (or slightly inclined) axis in the north–south direction and east-west rotation

- Gable structures are assumed with horizontal (or slightly inclined) axis in the north-south direction and towards east/west fixed module inclination (Tilt 25°),
- Radiation data (kW/m^2·y) and annual production (kWh/kWp·y) is evaluated for the location of Terralba, a small town in Sardinia, Italy;
- The PV potential estimation utility PVGIS [8], with solar database PVGIS-ERA5, has been used for the evaluation of the solar irradiation on the surface of the PV modules and to evaluate the annual electricity production.

Both conventional solutions are characterized by high land use that are about 13–14 m^2/kWp for the fixed shed solution, and 16–18 m^2/kWp for the solution with monoaxial trackers.

For the numerical comparison among the three different installation solutions, the following main technical and economic data was assumed:

- Available area: 50 ha (The hectare (ha) is not part of the International System of Units (SI), but is a measurement unit deeply embedded in history and culture, and currently widely used for land surface measurements. 1 ha = 10^4 m^2).
- Location: Lat. 39°42′ N, Long. 8°37′ E, with ground radiation of 1730 kWh/m^2·y.
- Photovoltaic module of 500 Wp (crystalline) with dimensions of ≈200 × 100 cm^2.
- Current unitary costs of the components of the PV systems (modules, inverters, structures, etc.).
- Extra current costs for: purchase of area, connection to the grid, auxiliary systems, technical and contractual expenses, etc.
- Current costs for annual management activities (maintenance, electricity consumption, insurance, periodic obligations, etc.).
- Sale of energy fed into the grid at the (constant) average unit price of 45 €/MWh in 2021, with an annual growth rate of 2%.
- Financial leverage of 70% for loans over 15 years, at current rates.
- NPC calculated at the interest rate of 3.00%
- Twenty-five-year business plan.

5.1. Annual Energy Production and Land Use Comparison

The comparison of energy production and footprint among the shed fixed-tilt, sun-tracking and gable structure is summarized in Table 1. The PV potential estimation utility PVGIS [26] has been used for the evaluation of the solar radiation on the surface of the PV modules. PVGIS-ERA5 database adopted is a solar radiation databases derived from climate reanalysis data. These solar radiation data have been obtained using numerical weather prediction models that have been corrected with data from meteorological stations, in order to make estimates of weather parameters for time periods in the past [23].

Table 1. Energy and land use comparison (50 ha land surface—50 × 10^4 m^2).

	Shed Fixed-Tilt	Sun-Tracking	Gable
Inverter oversizing	1.2	1.25	1.55
Annual energy production (kWh/kWp·y)	1640	1815	1365
PV array power density (MWp/ha)	1	0.836	1.713
Net Land Use (m^2/kWp)	10.47	11.96	6.05
Gross Land Use (m^2/kWp)	11.00	12.56	6.35
PV Plant size for 50 ha (MWp)	45.45	39.80	78.80
Annual energy production for 50 ha (GWh/year)	74.56	72.26	107.53

Annual/yearly energy production is the total amount of electrical energy the PV plant produces over a year, measured in kWh or MWh.

The total incident solar energy *H(τ)* on the modules can be evaluated according to (4)

$$H(\tau) = \int_{\tau} I(t)dt \tag{4}$$

where τ is the period of time (hour, day, year) and *I(t)* is the time variant solar radiation in kW/m^2 on the plane of the modules. By assuming τ is one year the (4) provides the annual/yearly incident solar energy on the surface of the modules in kWh/m^2 [14], that should be appropriately adjusted on the basis of the derating coefficients for not optimal modules inclination and orientation depending on local climate and latitude. Moreover, the electrical energy converted by the inverter, after taking into account the variability of the efficiency of the photovoltaic module in real conditions (effects on the efficiency of the module temperature of the module, variation of the internal resistance, mismatch, contamination, etc.), can be evaluated with (5) introducing the Balance of System Efficiency (BOS), which in turn is influenced by the time-dependent working conditions of the PV system [14].

$$E(\tau) = H(\tau) \cdot \eta_{BOS} \tag{5}$$

The following parameters have been used with PVGIS: system loss (η_{BOS}): 11%, changes in output due to angle of incidence: −2.57%, spectral effects: +0.85%, temperature and low irradiance: −6.49%, for a total loss of: ≈ −18.00%.

Further parameters have been also evaluated such as the PV array power density, that is equal to the PV array power deployable per unit of land area [8] considering an available terrain of 50 ha and the necessary spacing among arrays required to avoid shading effects and assumed equal to 5.2 m for the shed fixed-tilt, 3.2 m for single trackers and 2.6 m for the gable structure (25° inclination). An additional 15% of extra land is assumed for general services.

Regarding the land use of the solar plant the parameters (6) and (7) have been evaluated.

$$\text{PV Array Power Density}\left(\frac{\text{MWp}}{\text{ha}}\right) = \frac{P_{DC(STC)}(\text{MWp})}{\text{Land Area (ha)}} \tag{6}$$

$$\text{Land use per kWp installed}\left(\frac{\text{m}^2}{\text{kWp}}\right) = \frac{\text{Land Area }(\text{m}^2)}{P_{DC(STC)}(\text{kWp})} \tag{7}$$

According to the result of Table 1, the gable structure allows to install more power per unit of surface (≈97% more than the sun-tracking configuration) and therefore to produce annually a greater quantity of electricity (≈48% more than the sun-tracking configuration).

5.2. Economic Parameters Comparison

The Table 2 shows the results of the comparison with the different economic parameters that are generally used to analyze the effectiveness of an investment as described in Section 4 of the manuscript.

Table 2. CAPEX plant constructions subdivided by main components.

	Shed Fixed-Tilt	Sun-Tracking	Gable
PV modules (kEuro/MWp)	220	220	220
Mechanical structures and Mounting (kEuro/MWp)	175	215	170
D.C. main feeders and power cables (kEuro/MWp) and Mounting	10	10	8
Inverter (kEuro/MW$_{INV}$)	50	50	50
Inverter oversizing rate (kWp/kW$_{INV}$)	1.12	1.25	1.55
AC electromechanical systems (cables/substation/switchboards/transformers, etc.) and mounting (kEuro/MW$_{INV}$)	185	190	165

The CAPEX and OPEX considered in the following Tables 2–4 derive from estimates made by the authors for photovoltaic systems currently in the design, permitting, construction and operation phase in the Italian territory. The component prices are evaluated at the current date also from price quotations for the supply of materials for the construction of photovoltaic systems.

Table 3. CAPEX for land acquisition and grid connection.

	Shed Fixed-Tilt	Sun-Tracking	Gable
CAPEX ∝ Land Surface (kEuro/ha)	39	46	39
HV Connection infrastructure costs/TSO charges (kEuro/MW_{INV})	54.68	60.28	50.64

Table 4. Economic Comparison for PV Plants installed in a 50 ha land.

	Shed Fixed-Tilt	Sun-Tracking	Gable
CAPEX (kEuro)	32,118	29,450	46,900
OPEX (kEuro/y)	576	724	797
NPV (kEuro)	16,372	14,830	24,041
IRR (%)	12.14	11.99	12.20
LCOE (Euro/MWh)	35.62	36.90	35.35

In the CAPEX cost of Table 2 have been considered the costs strictly associated with the construction of the plant for modules, structures, DC and AC Cables, cable ducts and cable guides, electromechanical (transformers, switchboards, substations) components and accessories.

In addition, in Table 3 have been considered the costs proportional to the area (development, purchase, deeds, excavations, fencing, lighting, video surveillance, etc.) and the grid connection cost to the high voltage (HV) transmission network (purchase of areas, HV substation, HV power lines and cables) including the Transmission System Operator (TSO) connection charges.

The Tables 4 and 5 show the results of the comparison with the different economic parameters that are used to analyze the effectiveness of an investment as described in Section 4 of the manuscript.

Table 5. CAPEX and OPEX comparison in kEuro/MWp for PV Plants installed in a 50 ha land.

	Shed Fixed-Tilt	Sun-Tracking	Gable
CAPEX (kEuro/MWp)	706.67	739.95	595.17
OPEX (kEuro/MWp·y)	12.67	18.20	10.11

According to the result of Tables 4 and 5, the gable structure is the most advantageous in terms of LCOE, also thanks to the savings achievable with CAPEX and OPEX per MWp installed (due to savings in cables/inverters/transformers and no moving parts).

6. Conclusions

The paper provides a comprehensive and detailed study for a new fixed structure, named "gable structure with inverter oversizing", which can be advantageously adopted for ground and floating PV installations.

The techno-economic analysis provided in the paper is useful to compare the effective energy production of PV plants with different structural arrangements such as the conventional "fixed-tilt" and "sun-tracking" ground-mounted photovoltaic installations.

For the reasons set out in the article, the proposed solution should be carefully considered by the designers of photovoltaic systems each time that a new PV facility has to be developed, with the aim of optimizing the use and occupation of the land; especially in those situations where there are also further constraints, including the low agricultural productivity of the land, the presence of environmentally contaminated and/or compromised land, the presence of disused quarries and mines.

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