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Design and Feasibility Study of a Grid-Connected Photovoltaic Power Plant in Northern Italy: A Case Study in Trino, Piedmont

Relatori:

Prof. Filippo Spertino

Candidati:

Jad shakaroun

Politecnico
di Torino

1859

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1. Abstract

In last years the energy transition towards renewable energy became a global priority in order to combat climate change and ensure long-term energy security. According to European Union's climate objective and the United Nations sustainable development goals Italy should achieve at least 72% electricity generation from renewables by 2030[1]. Although renewable energy capacity is distributed across the country, Northern Italy which accounts for the highest electricity demand due to its dense population and industrial activity still depends heavily on electricity imports, particularly from France and Switzerland. To reduce electricity imports and improve regional energy self-sufficiency, it is essential to increase large-scale photovoltaic generation in Northern Italy, thereby contributing to national and EU climate goals.

This thesis discusses the design and feasibility assessment of grid-connected photovoltaic power plant in Trino (piedmont) . the aim of this project is to demonstrate how local renewable energy in northern part can reduce electricity imports from France and Switzerland which account for a significant portion of Italy's external energy supply valued at 6 € billion annually[3] . The plant design includes site selection , technical configuration ,performance simulation , and economic analysis comparing local solar generation costs to imported one.

In addition to evaluating the energy yield and cost-effectiveness , the thesis highlights the role of distributed solar infrastructure on lowering transmission losses , enhancing grid resilience and supporting regional energy autonomy ,the proposed PV plant demonstrates how renewable generation in northern part of Italy can contribute significantly to italy's 2030 goals , not only but cutting carbon emissions , but also to reduce the electricity imports and enhancing energy independence in its most industrialized regions.

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2. Italian Energy Context and the Transition Toward Renewables

2.1. The global energy transition

Over the last several years, as the effect of global warming increase fig.1 ,different procedures the world should done in order to address climate change , reduce carbons emissions ,and to secure a long term stable energy future . One of these procedure is the global energy transition, involves moving away from generating electricity from fossil fuels such as coal ,natural gas, and oil and going toward renewable energy sources such as solar, wind, hydro, and geothermal .

International frameworks such as the Paris Agreement and the United Nations Sustainable Development Goals (SDGs)—especially SDG 7 (Affordable and Clean Energy) and SDG 13 (Climate Action)—emphasize the need for a low-carbon global economy. Europe has responded to this call by launching the European Green Deal, which sets the ambitious goal of making the EU climate-neutral by 2050. As part of this strategy, the "Fit for 55" package requires member states to cut greenhouse gas emissions by at least 55% by 2030 compared to 1990 levels. These objectives are reshaping national energy plans and pushing industries, researchers, and policymakers toward innovative solutions that can deliver clean, resilient, and affordable energy systems.

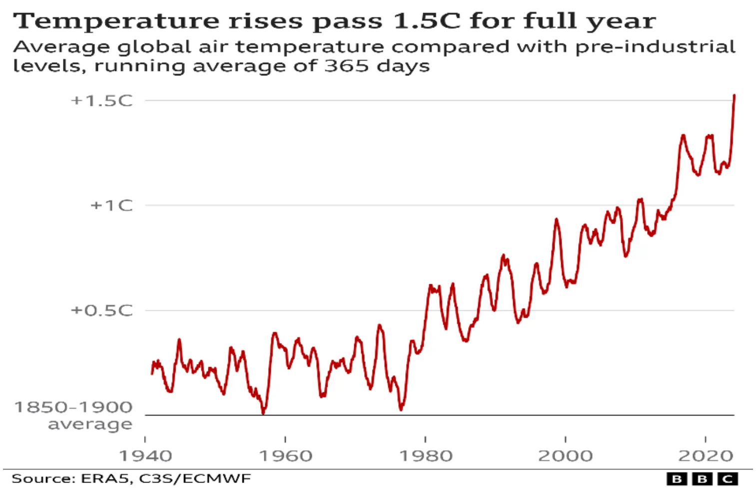

Figure 1 global warming between 1940 and 2020

2.2. Carbon Emissions and the Role of Renewables in Italy

As shown in Fig.2, Italy's carbon emissions have declined consistently between 2000 and 2023, as the nation advances its transition to a cleaner energy system. The decrease is largely the result of retiring coal, increasing energy efficiency, and the increasing share of renewable energy—particularly solar and wind—in the nation's mix of electricity. However, natural gas still supplies a high proportion of electricity and heat, especially in the north, which remains high in energy consumption and relatively low in local renewable generation. Raising the level of PV installations in these areas is paramount to continue reducing emissions, improve energy security locally, and meet EU climate targets under the Green Deal and Fit for 55. Solar PV, being a zero-emission technology at the operational phase, is one of the most effective solutions to eradicate emissions from the power sector and accelerate Italy's decarbonization pathway.

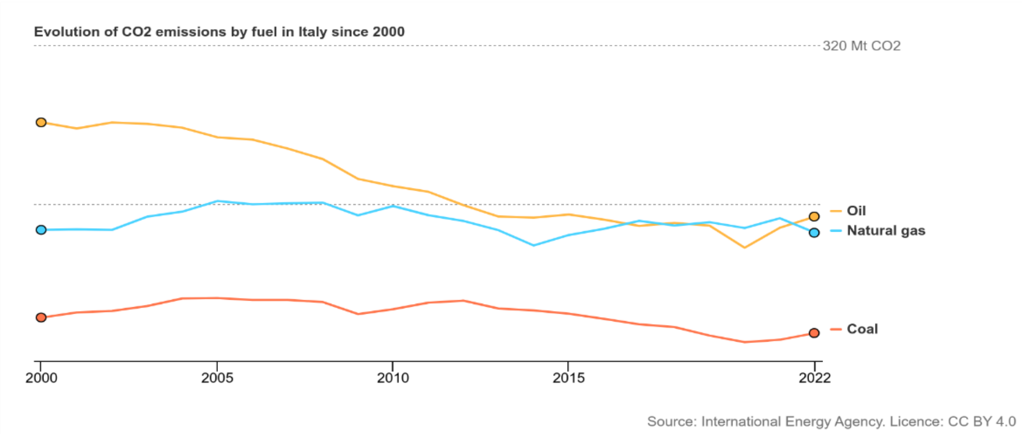

Figure 2 Evolution of CO2 emissions by fuel in Italy since 2000

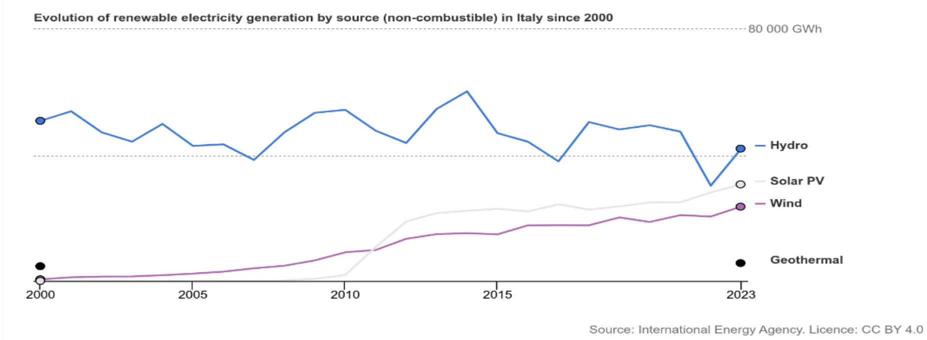

Figure 3 Evolution of renewable electricity generation by source (non-combustible) in Italy since 2000

2.3. Italy's Energy Strategy and Electricity Generation

According to International Energy Agency IEA Italy remains heavily dependent on fossil fuels fig.2, Natural gas accounted for 42% of total energy supply TES in 2021 (94% was imported) , Oil was ~33% of TES, with 92% imported ,where TES includes electricity generation, transport fuels ,heating fuels, industry(process heat..),regarding electricity generation only fossil fuels accounted for 55% for total generation. Overall fossil share (gas+oil+coal) was 71% of TES in 2023 – the lowest since the 1970s, reflecting strong renewables growth. Coal use has fallen sharply (coal generation is due to be phased out by 2025.[4]

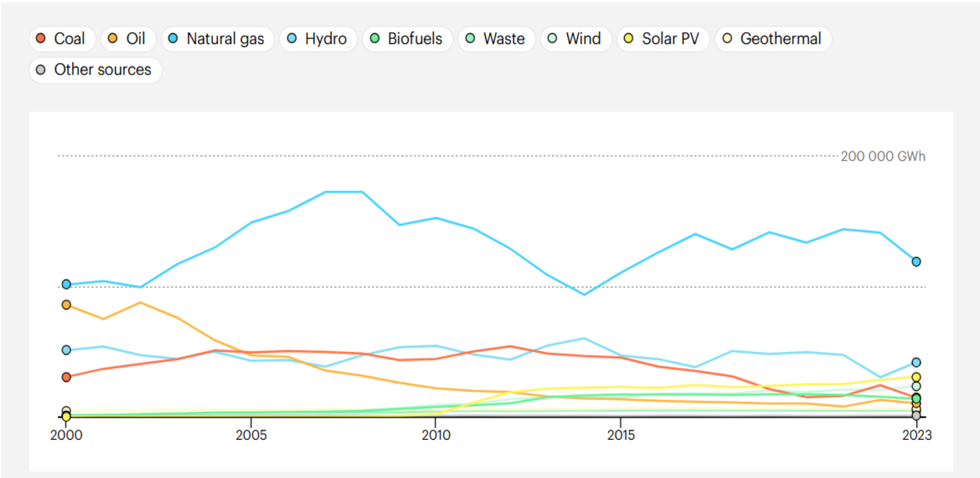

Figure 4 Evolution of electricity generation sources in Italy since 2000

Renewable electricity fig.3 reached new level in 2023 as reflection for the goal of Italy for 2030, wind and solar met ~17.5% of demand (up sharply with new capacity). Hydroelectricity is also significant (hydro rose +10 TWh in 2023). As a result, overall electricity from renewables surpassed any single fossil fuel source; In 2024, Italy's electricity demand was met with **42.5% non-renewables**, **41.2% renewables**, and the remaining ~16.3% from imports[5].

Import dependency: Italy imports a large share of its energy fig.5 In 2021 Italy imported ~1/3 of its fossil energy (e.g. 41% of gas imports came from Russia). In electricity, Italy remains a net importer: on average 2010–19 net imports were ~14% of demand (12% in the COVID-reduced year 2020, and back to ~14% in 2021, i.e. ~43 TWh). Electricity imports in 2021 came mainly from Switzerland (43% of net imports) and France (33%).

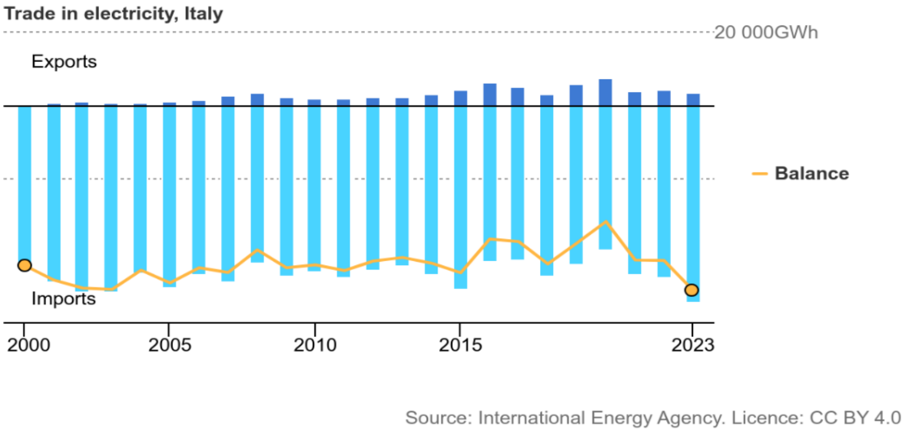

Figure 5 Trade in electricity, Italy

2.4. Renewable Energy Policies and National Goals

2030 targets : Italy's revised National Energy and Climate Plan (PNIEC, July 2024) set much more ambitious 2030 targets in line with EU Fit-for-55 and REPowerEU. It calls for renewables to reach ~39–40%[6] of final energy consumption, this includes electricity,heating, and transport sector. Also it calls for ~65% of electricity consumption by 2030[6]. . Italy has also legislated climate goals – e.g. carbon neutrality by 2050 (national law) and intermediate GHG reductions (Fit-for-55 alignment).

Key policies and plans: Italy implements EU directives via PNIEC (updated 2024) and deployment decrees. The government's Recovery and Resilience Plan (PNRR) channels billions to renewable projects and grids. Italy also adopted legislation affecting renewable siting and incentives. REPowerEU objectives – reducing gas import reliance – underlie increased renewables and efficiency measures (e.g. streamlined solar permitting). Regulatory schemes like feed-in tariffs, tax credits and aim to accelerate capacity builds. For example, the IEA notes Italy is on track to meet its NECP targets, but would need faster action to meet the new EU-enhanced targets by 2030

2.5. Growing importance of photovoltaic Energy

Rapid growth and capacity : the sector of photovoltaic has significant impact on the total energy generation , in 2023 , about 5.2 GW of new PV capacity was installed – the highest annual increase in a decade – bringing the total to 30.3 GW across ~1.6 million PV plants thanks to the small power plants installed at the rooftop/home and also for the incentives that government supply for people who installed a plant.

Regional distribution: PV deployment is uneven: by end-2023 about 48% of PV capacity was in Northern Italy (Lombardy, Veneto, Emilia-Romagna, etc.)[7], 17% in Central regions, and 27% in the South. In 2023 PV plants produced ~30.7 TWh[7] of electricity (partly offsetting high regional demand). As of 2024, renewables (largely hydro+PV+wind) covered ~41% of Italy's consumption, up from 37% in 2023.

2.6. Challenges and opportunities in Northern Italy

Demand vs local supply : the Northern part of Italy where is located all the industries and the heart of the population has high electricity consumption compared to southern or central part of Italy , although that there are many PV plants installed in northern part but still not sufficient for the demand Consequently, power flows from Southern Italy (and from abroad) northward during high-production periods, and Italy remains a net electricity importer overall.

Grid constraints and upgrade : Grid constraints and upgrades: North–south imbalance is constrained by transmission bottlenecks. Italy's narrow geography means power must travel long distances from significant solar/wind sites or imports. To address this, Terna's 2025–2034 plan allocates ~€23 billion to grid upgrade, including high-voltage DC "hypergrid" connections. Critical projects like the Tyrrhenian HVDC connection (Sicily–Sardinia–mainland) and Adriatic connection will raise cross-region transfer capacity from ~16 GW today to ~39 GW by 2030.These reinforcements are needed in order to supply more renewables towards the north and decongest. Overall, Terna emphasizes that the modernization of the grid is "essential to deal with increasing demand and integration of renewables" and to possess a strong backbone for firms and families

Land-use and siting limitations: In northern Italy, the development of large-scale photovoltaic (PV) farms is subject to strict land-use and siting regulations under national and regional regulation to balance energy transition goals with environmental and cultural protection. According to Legislative Decree 199/2021 a, PV installations are encouraged in suitable locations such as industrial zones, and along transport corridors, while they are banned in unsuitable locations such as high-quality agricultural land, Natura 2000 areas, and sites of historical or landscape significance. Local governments, such as Regione Piemonte.

These constraints aim to preserve the landscape and ensure responsible spatial planning, while also posing a challenge to the rapid expansion of solar energy in high-demand areas like northern Italy.

2.7. Importance of Local Generation in Northern Italy

Northern Italy is the economic and industrial heart of the country, hosting the highest concentration of manufacturing, commercial activity, and population density. As a result, it has the highest electricity demand across all regions. However, local renewable generation in the North remains relatively limited, especially from photovoltaic (PV) sources, due to factors such as lower solar irradiance, limited available land, and regulatory constraints. This has created a growing dependency on electricity imported from other parts of Italy and neighbouring countries such as France and Switzerland. Enhancing local renewable generation—particularly through utility-scale PV installations—can reduce this dependency, lower transmission losses, increase grid reliability, and improve regional energy security. Moreover, it aligns with national goals for decarbonization and the decentralization of energy systems, making it a strategic priority within Italy's broader energy transition.

3. State of the Art and Framework for Utility-Scale Photovoltaic Development in Italy

3.1. Overview of Photovoltaic Technology

3.1.1. Types of PV Cells and Modules

Modern solar PV fig.6 technology is dominated by first-generation crystalline silicon cells, which come mainly in two forms**: monocrystalline** and **polycrystalline** silicon[8]. Monocrystalline silicon cells are cut from single-crystal ingots and generally offer the highest efficiencies among commercial PV modules (typically in the 17–22% range). By contrast, polycrystalline silicon cells, made from cast blocks with multiple crystal grains, have slightly lower efficiency (commonly around 15–20%) but historically had lower manufacturing costs.In the past, polycrystalline panels were widely used due to cost advantages, but in recent years monocrystalline PERC (Passivated Emitter Rear Contact) and newer cell technologies have overtaken the market as cost differences narrowed and efficiency became paramount. A third category, **thin-film**[9]solar cells, represents second-generation PV technology and includes materials like amorphous silicon (a-Si), cadmium telluride (CdTe), and copper indium gallium (di)selenide (CIGS). Thin-film modules are made by depositing very thin layers of semiconductor on glass or flexible substrates, which reduces material usage. Commercial thin-film modules generally have lower conversion efficiencies (~10–12% for a-Si, up to ~18% for CdTe), although some high-performance thin-film cells (like gallium arsenide) have achieved much higher efficiencies in laboratory .In fact, single-junction thin-film GaAs cells have reached 29.1% efficiency in research, exceeding the ~26% lab record for single-junction silicon, and multi-junction cells (stacks of multiple thin-film layers) under concentrated sunlight have demonstrated efficiencies up to 47.6%.. Despite these impressive records, thin-film technologies account for only around 5% of global PV production as of 2023. Crystalline silicon remains dominant (~95% market share) due to its mature manufacturing and higher stability, but thin-film, especially CdTe, retains a niche in utility-scale projects (for example, in the United States, cadmium telluride modules comprised nearly 30% of new utility-scale PV installations in 2022).

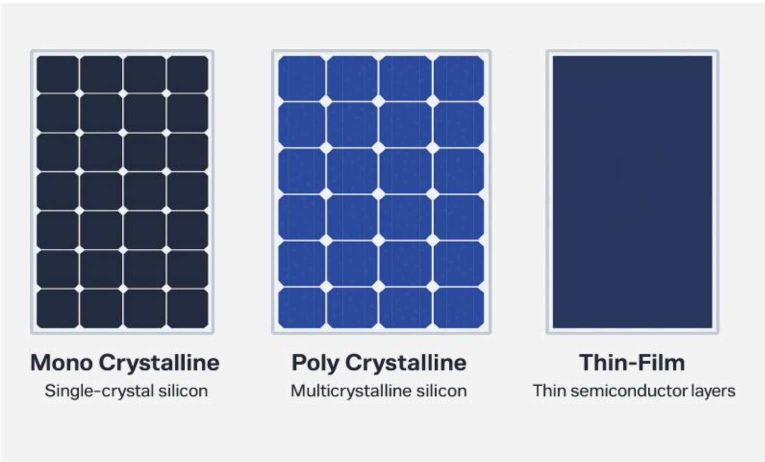

Figure 6 types of PV cells

3.1.2. Module Efficiency Benchmarks

The efficiency of PV modules – the percentage of sunlight converted to electricity – has steadily improved over the past decade. According to Fraunhofer ISE, the world's leading PV manufacturers achieved commercial module efficiencies ranging roughly from 19% up to 23–24% by 2024, with a weighted average around 22.0% for crystalline silicon modules. Just a year earlier, the range was lower (17.4% minimum, 23.3% max in late 2023), reflecting rapid progress as manufacturers transition to new cell architectures. In practical terms, state-of-the-art monocrystalline modules available today (2025) can exceed 22–23% efficiency under standard test conditions, meaning a typical 2 m^2 panel might output around 400–450 Wp. Polycrystalline modules tend to lag a few percentage points behind (mostly 15–19% efficient), though they are becoming less common. Thin-film modules (like First Solar's CdTe series) have achieved around 18–19% in mass production.

3.1.3. Inverter

In a photovoltaic system, the inverter is a vital power electronic converter that converts the direct current (DC) electricity generated by solar panels to alternating current (AC) electricity and can be supplied back to the grid or local loads. The inverter performs by using semiconductor switches (usually IGBTs or MOSFETs) that rapidly switch the DC input on and off in a controlled manner, producing a pulsed output which is filtered and regulated to a clean sinusoidal AC waveform. Inverters today also include Maximum Power Point Tracking (MPPT) algorithms to constantly adjust the operation voltage of the PV array so that it provides the maximum available power in fluctuating environmental conditions. In addition to conversion, inverters perform many basic functions: monitoring and diagnostics, grid synchronization, power factor correction, and anti-islanding protection for grid security

DC/AC Conversion Efficiency: The DC/AC efficiency of an inverter is the ratio of AC output power to DC input power from the PV array. This efficiency is a function of a number of parameters, including input voltage, inverter load level, ambient temperature, and internal losses,it can be calculated using equation 1. Most high-quality inverters on the market today have peak efficiencies between 97% and 99%, although this value varies slightly by system size and technology (string, central, or microinverters).In order to better represent field operation, the European efficiency measure is often used. It calculates a weighted average of inverter efficiency at different partial load levels fig(7)(e.g., 10%, 20%, 50%, 100%), which better represents the performance of PV systems over the period of a day and over the seasons.

$$\mu_{DC/AC} = \frac{P_{AC}}{P_{DC}} = \frac{P_{AC}}{P_{AC} + P_{loss}} \qquad eq(1)$$

Maximum Power Point Tracking (MPPT) Efficiency: In addition to conversion, inverters also incorporate Maximum Power Point Tracking (MPPT) algorithms fig(8). These dynamically regulate the operating voltage and current of the PV array to stay at the maximum power point, which changes with solar irradiance and temperature. MPPT efficiency is usually greater than 98%, so a very small amount of potential power is lost due to imperfect tracking. Some advanced inverters have more than one MPPT input, where different PV strings with different orientations or degrees of shading are optimized separately.

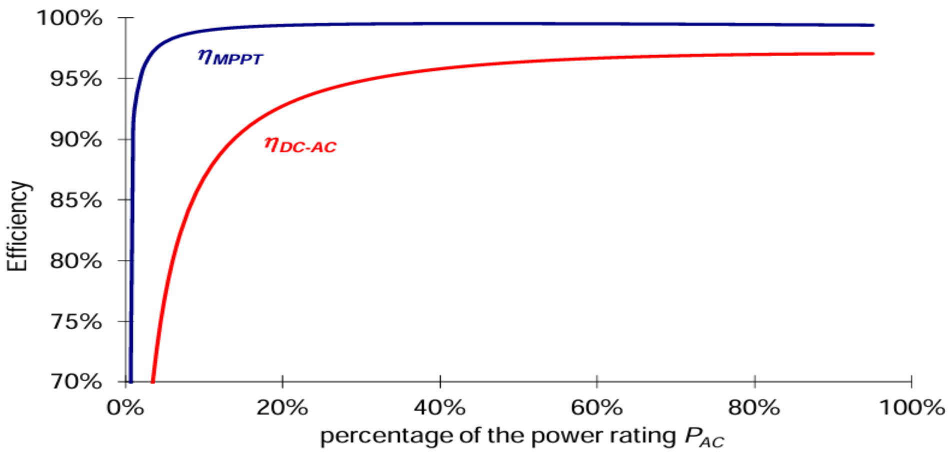

Figure 7 efficiency of DC/AC conversion and MPPT

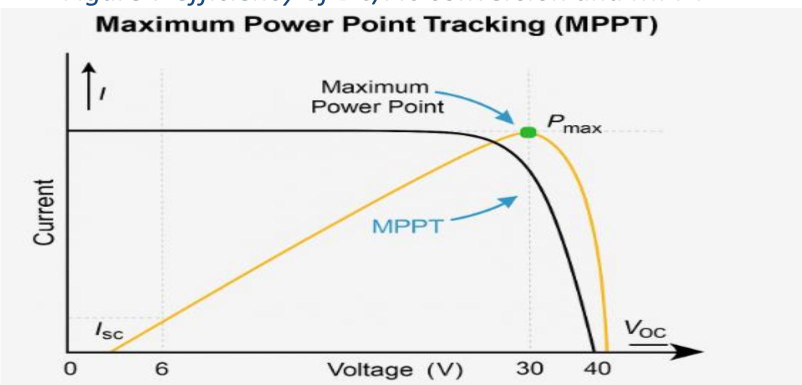

Figure 8 MPPT TRACKING

Inverter type: **Central inverters** (1–5 MW each) handle many PV strings at once and are usually placed in centralized stations. They're cost-effective and simplify design but present a single point of failure—a fault can shut down a large plant section, and repairs may require specialized equipment.
String inverters (typically 50–350 kW each) are distributed across the array and manage smaller groups of panels. They offer better fault tolerance (only one string goes offline in case of failure), easier maintenance, and multiple MPPT inputs, improving performance on uneven terrain or with partial shading. Due to increasing power ratings, string inverters are now widely used even in large (>100 MW) plants.
Microinverters are used mostly in residential systems and are not practical for utility-scale projects due to cost and high component count.

3.1.4. Current Efficiency and Performance Benchmarks

Beyond module conversion efficiency, another important point is the expected energy yield or performance ratio of a PV plant. Under standard test conditions, a 1 MWp array produces 1 MW under 1000 W/m² irradiance at 25°C cell temperature. In real operating conditions, factors like temperature, soiling, wiring losses, and inverter efficiency mean that the actual AC output is lower. Most modern utility plants have a performance ratio in the range of 80–90%, meaning they convert 80–90% of the incident solar energy (under reference conditions) into exported AC energy after all losses.

3.2. Utility-Scale Solar Plants: Global and European Trends

Utility-scale solar power stations are enormous photovoltaic (PV) arrays designed for the sole intention of feeding electricity into the grid, rather than being used on-site for self-consumption. Installations typically range between 1 megawatt (MW) and more, with most modern stations having capacities above 50–100 MW. In contrast to residential or rooftop installations, utility-scale installations are built on open land, often using ground-mounted arrays and are directly connected to the medium- or high-voltage transmission system

3.2.1. Global Installation Trends

Worldwide Installation Trends: Solar PV is the fastest-growing form of electricity generation worldwide over the last few years. Cumulative installed solar PV capacity worldwide crossed the 1 terawatt (TW) threshold in early 2022, and growth further accelerated in 2023. The planet installed a record 346

GW of solar PV in 2023[10], bringing the global total to around 1.42 TW of solar capacity by the end of the year, according to the International Renewable Energy Agency (IRENA). This 32% jump in one year made solar the world's biggest renewable generation technology by installed capacity, overtaking hydropower globally.

3.2.2. Design Practices and Land Use

Utility-scale solar design is continuously evolving to maximize energy yield and minimize costs. One key consideration is whether to use fixed-tilt or tracking .Globally, there has been a strong shift toward single-axis tracking for large plants in sunny regions.

Land use is a critical aspect of utility PV deployment. Solar farms require substantial area, though not as much as some assume. Typical land requirements are on the order of 1.5 to 2 hectares per MWp for a fixed-tilt system, or roughly 5–7 acres per MW[11].

In Italy, land use and permitting are the key drivers for utility-scale PV development. Plants are typically located on low-yielding agricultural lands, brownfields, or disturbed areas such as quarries or landfills to reduce permitting issues. A typical plant requires a site of about 2 hectares/MW, thus a 100 MW plant can cover ~200 ha. Developers increasingly consider agrivoltaic systems or marginal lands in order to balance energy production with land conservation.

3.2.3. Advantages and Challenges of Utility-Scale PV

Large-scale photovoltaic (PV) power plants offer several advantages that make them a cornerstone of the energy transition. They provide low-cost electricity, with falling installation costs and no exposure to fuel price risk. PV power plants are also clean, with zero emissions during operations and very low life-cycle carbon footprints—over 90% lower than coal-based power. They are modular and scalable systems with incremental capacity additions feasible and relatively quick deployment; e.g., a 50 MW solar farm can be built in 6–12 months after permitting. Moreover, solar energy enhances national energy independence by displacing imported fossil fuels.

Despite these benefits, utility-scale PV faces several challenges. Its intermittency implies that solar output varies with weather and time of day and requires storage or backup for grid reliability. Integration into the grid is also a concern, particularly if generation is concentrated in remote high-irradiance areas (e.g., southern Italy) and demand is higher elsewhere (e.g., the North), which strains transmission networks. Other issues are land use conflicts, especially where agricultural land or scenic views are conserved, and regulatory challenges, as permitting is delayed by complex environmental reviews.

3.3. Italy’s Solar Policy Framework and Incentives

Italy was one of the early adopters of solar energy in Europe, experiencing a solar boom in the 2010–2013 period under generous feed-in tariffs. The policy landscape has since evolved considerably. This section outlines the major policies, incentives, and regulatory factors shaping utility-scale PV development in Italy, including the role of GSE (the state energy agency), the historic Conto Energia feed-in tariff programs, recent auction schemes (known as Decreto FER auctions), support from the EU-funded PNRR (National Recovery and Resilience Plan), as well as regional permitting and land access considerations. Understanding this framework is crucial, as it influences project viability, site selection, and design (for instance, favoring certain technologies like agrivoltaics or storage integration).

Italy has developed a comprehensive policy framework to support the growth of renewable energy, particularly photovoltaic (PV) systems, to support national energy transition and EU climate goals. The GSE (Gestore dei Servizi Energetici) is in charge of regulating renewable energy support schemes, including incentive schemes, management of energy accounts, and auctions. Previously, the Conto Energia program (2005–2013) was the main driver to scale up PV through offering favourable feed-in tariffs, which led to the rapid installation of over 17 GW of capacity. Although the Conto Energia program has been withdrawn, the policy landscape continues to promote solar deployment through the application of organized auctions and simplified permitting procedures.

Among the principal active tools is the FER 1 Decree, providing incentives for renewable power plants through competitive auctions and registration mechanisms, mainly for plants with a capacity of more than 1 MW. It enables the buying of electricity at fixed tariffs or through contracts for differences (CfDs). Moreover, Italy's National Recovery and Resilience Plan (PNRR) spends billions of euros of EU recovery money on renewable energy initiatives, including grid improvement and solar integration. For small power plants, especially rooftop and marginal land power plants, there are simplified authorization schemes (PAS) and tax credits for self-consumption. Agrivoltaics are also being encouraged by the government, driving PV installation on farms with minimal disruption to agriculture. Despite that, developers still face challenges such as bureaucratic delays, local permit inconsistencies, and grid connection shortages, particularly in high-demand regions such as Northern Italy.

3.4. Grid Integration, Storage, and Intermittency Challenges

As photovoltaic (PV) energy becomes an increasingly important component of the electricity mix, new challenges emerge related to its integration into the existing power grid. Unlike conventional generation, solar power is inherently variable and intermittent—depending on weather conditions and daylight hours—which can lead to fluctuations in output that must be carefully managed to maintain grid stability. Moreover, the large-scale deployment of PV, especially in regions far from major demand centers, places pressure on transmission infrastructure and may cause congestion or energy curtailment.

3.4.1. Intermittency and Variability

Solar PV output is inherently variable – it follows a bell-curve daily pattern on sunny days (zero at night, ramping up in the morning, peaking at solar noon, and dropping to zero at dusk), and is reduced on cloudy days. Seasonally, output is higher in summer and lower in winter due to sun angle and day length (especially at Northern Italy's latitude ~45°N, winter yields are perhaps one-third of summer yields). For a grid operator, this variability introduces challenges in balancing supply and demand. On a clear summer day, a large PV plant will have a steep morning ramp-up and an equally steep evening drop-off, which other power plants or storage must accommodate. In Italy, as solar capacity has grown, the net load curve (load minus solar) in midday has dipped significantly, resembling the famous "duck curve" shape seen in California. Managing these ramps and ensuring backup in the evening (when solar is gone but demand may still be high) is a critical issue. This is one reason Italy, like other countries, is investing in storage and flexible generation.

3.4.2. Grid Balancing and Curtailment

With high solar output at noon, there can be times when supply exceeds demand or when network capacity is insufficient to transport the power. In such cases, curtailment (forced reduction of PV output) can occur. Already in Southern Italy and Sicily, experts projected curtailments reaching a few percent of total renewable generation due to grid constraints. Curtailment usually happens when the grid is congested , so some farms are asked to reduce output. Curtailment is not only a loss of potential green energy but also an economic loss for plant owners Solutions to reduce curtailment include strengthening the grid and adding demand flexibility (like incentivizing industrial use or EV charging at noon) or storage to absorb the midday surplus.

3.4.3. Reverse Power Flow in Distribution Networks

Most distribution grids medium voltage feeders were built to deliver power from the transmission grid to end-consumers. Now with many PV plants and also rooftop solar connected at medium or low voltage, power can flow in reverse from the PV site back up to the higher voltage network especially during low local load and high sun. This can cause voltage rise issues on distribution lines and even cause protection devices to misoperate if not adjusted. Distribution operators (DSOs) in Italy have been upgrading equipment adding remote voltage regulation, changing transformer set-points to cope with this.

3.4.4. Italy's North–South Transmission Constraints

One of the specific issues in Italy is that the southern regions (e.g., Sicily, Sardinia) have high renewable potential (sun and wind) but relatively lower local demand, whereas the north (Lombardy, industrial regions) has huge demand but less renewables. This geographical mismatch means power has to flow northward. The current grid has several "market zones" separated by transmission limits. Frequently, the southern zone has excess generation causing price splitting (lower prices in south, higher in north) and renewables curtailment in the south because not all energy can be shipped to the north at that moment.

4. Site Selection & Location Analysis

The feasibility and performance of a utility-scale photovoltaic (PV) plant are strongly influenced by site-specific factors such as solar irradiance, land characteristics, grid proximity, and regulatory conditions. This chapter presents a comprehensive analysis of the proposed installation site in Trino, Piedmont, evaluating its suitability for hosting an 80–120 MW PV plant. Located in Northern Italy,Trino offers strategic advantages including proximity to high-voltage infrastructure, availability of non-agricultural land, and acceptable solar resources. Using tools such as PVGIS for resource assessment and Geoportale Piemonte for zoning and environmental data, this chapter outlines the technical, environmental, and regulatory rationale for selecting the site and confirms its compliance with Italy's national and regional energy planning frameworks.

4.1. Why Trino?

Energy Context and Demand: Trino is located in northwest Italy (Province of Vercelli, Piedmont) and was chosen as the site for an 52MW class solar PV plant due to a combination of national and local factors. Italy has a high dependence on imported energy. This includes a significant share of electricity imports historically around 10–15% of Italy's power consumption primarily from France and Switzerland. Building a large solar facility in Italy helps reduce reliance on imported electricity. In particular, northern Italy is a major load center that can benefit from more local generation. The Trino project is expected to produce 64 GWh per year of clean electricity, enough to supply 21000 households. This substantial output directly supports Italy's decarbonization goals and will displace a portion of fossil-fuel generation and imports.

Historic Energy Site with Infrastructure: Trino was selected in large part because the site is historically an energy generation hub. Until 1987[12], Trino hosted one of Italy's few nuclear power stations (the Enrico Fermi NPP, 260 MW) which was shut down after Italy's referendum banning nuclear energy .Subsequently, Italy's first combined-cycle gas power plant, the 1300 MW "Galileo Ferraris" station[12], was built on or adjacent to the same site in the 1990s. The Galileo Ferraris CCGT plant operated until 2013, after which it was decommissioned, leaving behind an expansive brownfield site with existing grid infrastructure. This legacy makes Trino uniquely attractive for a new utility-scale solar farm. The previous power plants had high-voltage grid connections in place (a 220/380 kV transmission substation serving the site), which can now be leveraged by the solar farm. Reusing an established grid interconnection dramatically simplifies the project's grid integration and reduces costs and permitting complexity for new transmission lines. In addition, the electrical and road infrastructure from the former plants (such as access roads, fencing, and possibly buildings or utilities) can be repurposed or already meet industrial standards, facilitating the construction and operation of the PV facility**.**

High Solar Irradiance Potential: Although northern Italy has slightly lower solar radiation than the south, the Trino site still enjoys strong solar irradiance, characteristic of the Po Valley's climate. The region's flat plains receive sufficient sunshine especially in summer. In fact, according to PVGIS data for Trino fig (9), the area receives on the order of 1,500 kWh/m² per year of global horizontal irradiation (GHI) on average, which is a robust solar resource .

When panels are tilted at the optimal angle 38° tilt in this location , the annual irradiation on the module surface can reach roughly 1,800 kWh/m² fig(10) . This indicates that Trino's solar resource is quite favorable not as high as Sicily or southern Italy, but among the better locations in northern Italy for PV. The site's latitude (~45°N) yields long summer days and decent winter sun; monthly GHI ranges from about 30–80 kWh/m² in winter months up to ~190–230 kWh/m² in the peak summer months fig (9) . Such irradiance levels make a solar farm economically viable.. In summary, Trino offers sufficient solar resource to support a large PV installation, and this is a key reason the site was chosen.

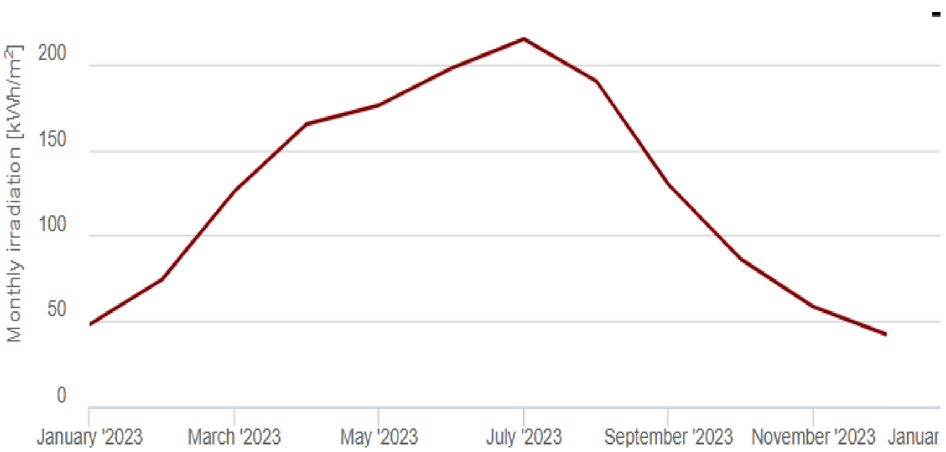

Figure 9 Monthly solar irradiation estimates in Trino

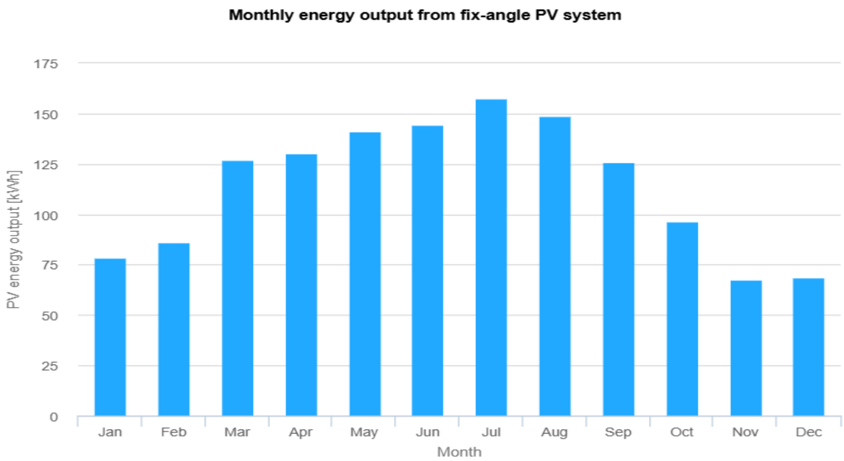

Figure 10 Monthly solar irradiation estimates with optimal tilt angle 38

Existing grid infrastructure fig.11**:** A critical factor in site selection is the ability to connect to the power grid. The former power plants at Trino were hooked into the high voltage transmission network, so the grid infrastructure is already in place. There is an existing electrical substation and high-voltage lines . This means the new solar farm can feed its power into the grid with relatively minor upgrades as the grid will be beside the solar farm . Utilizing an existing grid connection significantly reduces costs and delays compared to a remote site that would require building new long high-voltage lines or substations. The Trino project's success indeed hinged on this advantage – by siting the PV on a former generation site. Additionally, the grid at Trino is robust it was designed for a large continuous power output, which helps in integrating the intermittent solar output. The presence of a major grid node also makes it feasible to add battery storage on-site to provide ancillary services . In short, Trino was chosen because it offered a rare combination of strong grid connectivity and available land, making it an ideal location to deploy significant solar capacity quickly and efficiently.

Figure 11 grid infrastructure near the designed solar plant

4.2. Solar Resource Assesment

To quantify Trino's solar potential, a solar resource assessment was performed using the Photovoltaic Geographical Information System (PVGIS) database. PVGIS provides long-term satellite-based climate data for solar irradiation and PV performance across Europe. For the Trino site, PVGIS data (using the SARAH radiation dataset) were retrieved to understand monthly and annual solar energy availability. Key findings from the PVGIS analysis include:

Optimal Tilt and Orientation: To determine the optimal tilt angle for the proposed photovoltaic installation in Trino, I performed a series of simulations using the PVGIS tool at the site coordinates (45.1842° N, 8.2819° E). Five different fixed tilt angles were evaluated: 30°, 32°, 34°, 36°,38°, and 40°fig (12), all with a south-facing orientation (azimuth = 0°). The simulation results showed a progressive increase in annual energy yield with higher tilt angles, with 38° providing the highest output in terms of specific yield (kWh/kWp). Based on this analysis, a fixed tilt of 38° was selected as the optimal configuration for maximizing energy production under the site's solar resource conditions.

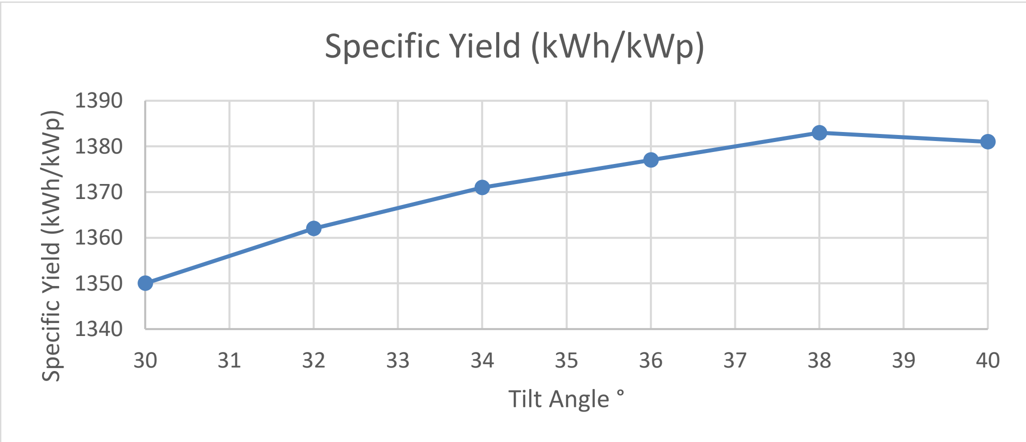

Figure 12 optimal tilt angle

Irradiation on Tilted Plane: When panels are tilted at the optimal 38°, they intercept more sunlight annually than a horizontal surface. The annual irradiation on an optimally inclined plane is about 1,750–1,800 kWh/m² at Trino . This is ~20% higher than horizontal, thanks to better capture of winter sun at a tilt and near-normal incidence in summer. For instance, in January an optimally tilted panel might receive ~90–120 kWh/m² (versus ~50 kWh/m² horizontal), and in July ~210 kWh/m² (similar to horizontal since summer sun is high) . These data confirm that using tilted mounting substantially boosts energy yield over the year.

Temperature: The average ambient temperature at Trino ranges from ~1–4°C in winter to 23 27°C in peak summer , according to PVGIS monthly mean 24-hour temperatures (T2m). These moderate temperatures are beneficial for PV performance though peak summer heat can slightly reduce panel efficiency. Still, the climate is generally temperate with hot summers and cool winters, requiring consideration of panel cooling and possible minor performance drop in July/August.

Overall, the PVGIS assessment confirms that Trino has an excellent solar resource for a northern Italian location, with clear skies and high irradiance especially in late spring and summer. The data justifies the site selection from a solar energy perspective, ensuring the PV plant will operate at a high output. These figures provide confidence in the project's feasibility, guiding the design selecting a 38° tilt and south orientation to maximize annual yield and forecasting the energy contribution of the Trino solar farm to the grid.

4.3. Land Characteristics: Flatness, Zoning, and Accessibility

Topography – Flat Terrain: The Trino site lies in the Po River plain, which is an almost completely flat lowland. This flatness is ideal for a solar installation. A flat site simplifies engineering and construction, large arrays of panels can be installed on level ground without the need for extensive terracing or complex foundations. It also means minimal shading from terrain no hills or mountains block the sun's path. The area around Trino is open farmland and former industrial land, so the horizon is largely clear. PVGIS horizon profiles indicate no significant terrain shading issues at this latitude . The flat ground also facilitates maintenance and cleaning of panels and allows efficient use of tracking systems. In summary, the site's flatness provides optimal solar exposure and easy constructability, reducing costs and maximizing energy capture.

Land Use and Zoning: As noted, this land has a long history of energy infrastructure. It is zoned for power generation/industrial use, not residential or pristine agricultural. The nuclear plant occupied a substantial plot, and later the gas plant and now the PV farm utilize that footprint. This means there were few competing land-use concerns the community and authorities already designated this site for electricity production decades ago. Using it for solar is consistent with that designation. Moreover, by installing PV panels on the existing site ,the project avoids converting new farmland. This is important in a rural province like Vercelli, known for rice and crop fields the PV park did not eat into active cropland but instead sits on an "already developed" piece of land.

Accessibility and Infrastructure: The Trino location is well-connected and accessible, which is a practical advantage for construction and operation. The site lies a few kilometers from the town of Trino and not far from major roads: it can be reached via provincial highways that link to the A4 Turin-Milan motorway and other regional roads, facilitating the transport of solar panels, inverters, batteries, and construction equipment. During its time as a nuclear and gas plant, infrastructure was developed to access the site, including roads capable of handling heavy machinery (for reactor components, fuel delivery, etc.). These same access ways could be used or upgraded for the solar project, meaning logistics were relatively straightforward.

Flatness & Design Implications: The combination of flat land and lack of significant regulatory height restrictions meant the project could install row after row of panels with optimal spacing and tilt. The flat terrain allowed the design to maintain consistent tilt angles and azimuth across the whole array, simplifying energy modeling. It also made it possible to consider single axis trackers. In short, the land characteristics at Trino flat, stable, accessible, and already industrial provided an excellent foundation for the solar park's layout and construction.

5. System design

5.1. Methodology and Software Environment

The simulation and design of the proposed 52 MWp utility-scale photovoltaic (PV) solar power plant were carried out through a structured and software-based methodology. The methodology was divided into a series of steps so that correct terrain modeling, simulation of maximum energy, and compliance with spatial as well as technical constraints can be ensured.
The initial project step involved defining the usable area of each of the seven stand-alone regions. The land limits and availability were mapped first, using AutoCAD fig(13) , for easy measurement and division of the land. These maps were then imported and exported to Solarius PV, a commercial PV design software provided by ACCA Software.
Solarius PV was selected because it comes with an integrated environment that supports:

- 3D terrain modeling from imported CAD topography ,
- Detailed PV module layout configuration,
- Electrical array design and inverter selection,
- Yearly shading simulation,
- Calculation of energy production and system loss,

• Performance assessment metrics such as BOS efficiency, specific yield, and clipping analysis.

The package enabled high-resolution simulation of every zone on the basis of realistic limitations such as module spacing, tilt, and row orientation. It also enabled fine-scale measurement of every zone's energy performance based on past irradiance and temperature data.

The following subsections detail the step-by-step methodology adopted for system modeling, from layout definition to simulation outcome, and illustrate screenshots of the software interface to explain the design process.

Figure 13 Autocad design

5.2. Plant Capacity and Zonal Configuration

The proposed photovoltaic (PV) power plant is divided into seven zones across the available site in Trino.

Table 1 shows the DC capacity (module power installed) and AC inverter capacity per zone and module and inverter quantities. The overall plant is composed of a sum of a total DC capacity of approximately 51.3 MWp and an overall AC capacity of 42 MW

(42 inverters, each with a capacity of 1 MW_AC). DC/AC (oversizing) ratio varies across zones from about 0.94 to 1.38, a value which reflects differences in land availability and design choice for each zone. A DC/AC ratio of above 1.0 indicates DC "oversizing," where the PVmodule nameplate rating is above the inverter nameplate rating – this will result in increased energy output at the cost of some power clipping during maximum periods (later examined), and a ratio below 1.0 indicates that the inverters are under maximum use by the DC array in that locale.

Zone	DC Capacity (MW_p)	AC Inverters (MW_AC)	DC/AC Ratio	No. of Modules	No. of Inverters
1-a	6.2115 MW_p	5 MW_AC	1.24:1	12300	5
1-b	3.0199 MW_p	3 MW_AC	1.006:1	5980	3
2	4.69044 MW_p	5 MW_AC	0.94 : 1	9,288	5
3	9.32129 MW_p	7 MW_AC	1.33 : 1	18,458	7
4	8.25372 MW_p	6 MW_AC	1.38 : 1	16,344	6
5-a	9.26877 MW_p	7 MW_AC	1.32 : 1	18,354	7
5-b	2.68610 MW_p	2 MW_AC	1.34 : 1	5,319	2
6	1.93718 MW_p	2 MW_AC	0.96:1	3836	2
7	5.91254 MW_p	5 MW_AC	1.18:1	11708	5

Table 1 Zone-wise PV array sizing and inverter configuration.

The overall plant DC/AC ratio is ~1.22 (51.3 MW_p / 42 MW), a moderate oversizing level typical for utility-scale PV projects to maximize energy yield. In total, approximately 102,000 PV modules are used across the Seven zones (summing the module counts in Table 5.1), and 42 inverters (each 1 MVA) are deployed for grid connection.

Each zone can be considered a sub-array with its inverters and transformer station. By segmenting the plant into zones, the design can account for slight differences in site conditions (shape of the land plot or cable distance) and optimize inverter placement within each zone. All zones are connected to the central grid interface, but operate independently in the DC sense – this modular zoning improves reliability and maintainability (if one zone is offline, others are unaffected).

5.3. Photovoltaic Modules and Array Characteristics

Module Selection: The PV modules selected for this project are Trina Solar Vertex S+ TSM-NEG18R.20 fig.14 panels, with a rated power of 505 Wp (at Standard Test Conditions) fig(15),fig(16). These are high-efficiency monocrystalline N-type i-TOPCon cell modules with a dual-glass. Each module has a certified efficiency of 22.9% at 505 W output , placing it among the top performers in the market. The choice of this type was driven by its superior performance and durability: N-type cells have lower light-induced degradation and better temperature coefficients than conventional P-type cells. In fact, the module's temperature coefficient of power is only –0.29%/°C , meaning the loss of output in hot conditions is relatively low (improving energy yield in summer).

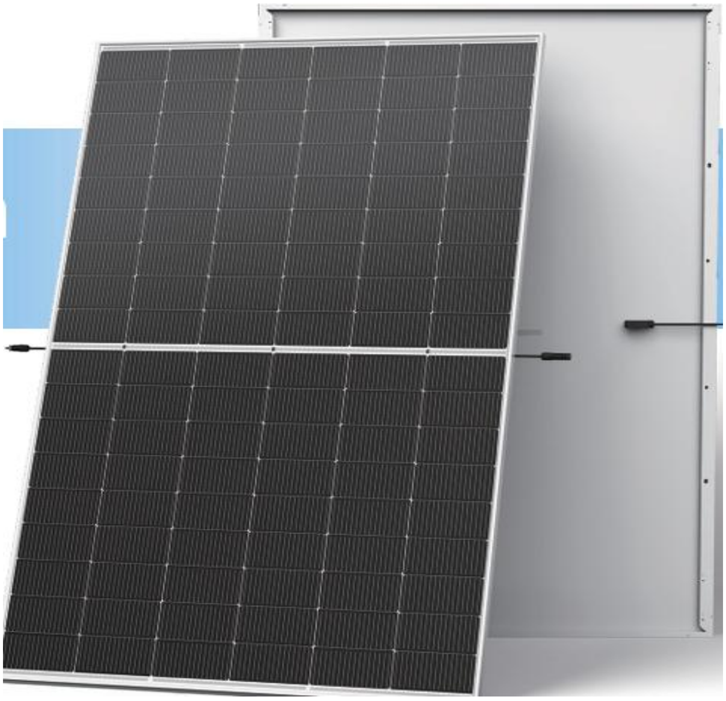

Figure 14 :Trina Solar Vertex S+ TSM-NEG18R.20

Electrical Specifications: Each module consists of 108 monocrystalline silicon cells (half-cut configuration) in a 210 mm wafer format. At STC, the 505 Wp module's maximum power voltage V_{MPP} is about 33.5 V and current I_{MPP} is 15.09 A . The open-circuit voltage V_{OC} is approximately 40.3 V and short-circuit current I_{SC} is 15.9 A . Modules are rated for up to 1500 V DC systems , which allows long strings and

efficient array design. The module’s performance at lower irradiance is also strong – it is designed for excellent low-light efficiency and has an NOCT (Nominal Operating Cell Temperature) around 43 °C , indicating good thermal behavior.
Each module measures 1.961 × 1.134 m (approximately 2.23 m² area) and is only 30 mm thick . Despite the large size and glass-glass build, the module weight is moderate at 23.5 kg , which eases handling during installation. The dual 2 mm glass layers (front and back) provide improved durability: the module can withstand up to 5400 Pa front load (e.g. snow) and 2400 Pa back load (wind uplift) . Trina Solar guarantees a first-year degradation ≤1% and linear annual degradation of 0.4%, retaining ~87% of output after 30 years – this extended performance warranty is advantageous for a long-term project.

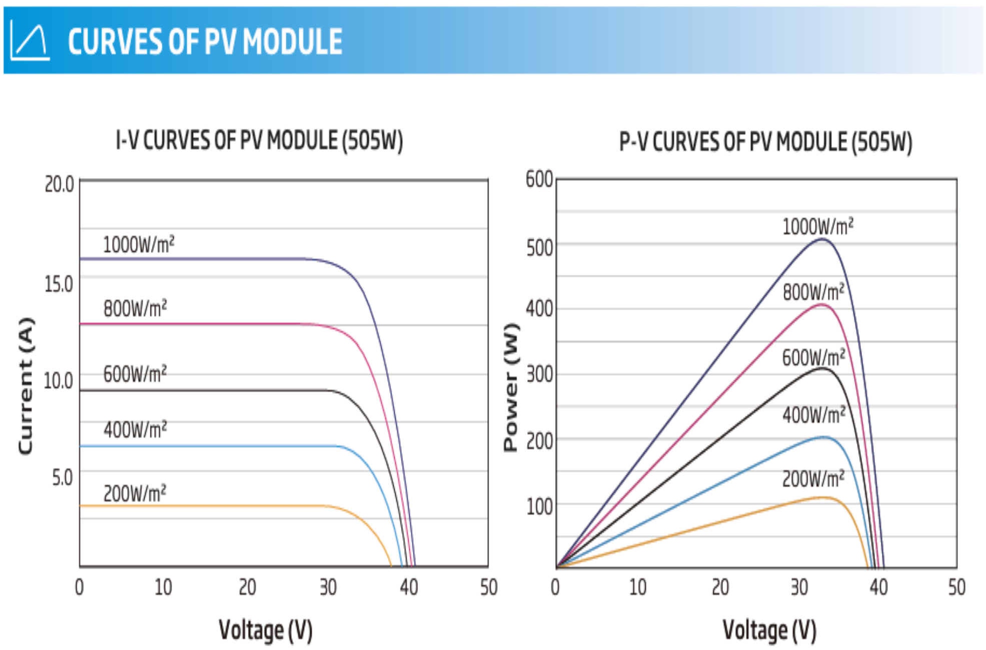

Figure 15 I–V curve of Trina Vertex S+ module at STC

Array Configuration: The modules are mounted in fixed-tilt arrays and wired in series strings to achieve the desired array voltage. Based on the 1000 V DC limit and the module V_{OC}, each string in this design uses more or less 19 modules in series. At the coldest expected temperature (around –10 °C in Piedmont winters), the string open-circuit voltage will rise (due to the negative temp. coefficient), but 19 × V_{OC} ≈ 19 × 40.3 V = 765.7 V (at 25 °C) which even when corrected for –10 °C remains safely under 1000 V (this was verified with a margin in the design calculations). At the other extreme, at high module temperatures the string voltage will drop – but 19 modules still provide sufficient voltage for the inverter MPPT window (the inverter requires >530 V, see Section 5.4). Thus, 19-module strings are a suitable choice to maximize string length while respecting the inverter's 1000 V input limit . All modules in a string are identical and oriented at the same tilt, minimizing mismatch losses.

Total number of strings per zone depends on the zone's module count. For example, Zone 3 with 18,458 modules has 966 series strings (each 19 modules) feeding its inverters . Similarly, other zones have on the order of 900–970 strings for the 7 MW zones, ~420–450 strings for 5 MW zones… Each string is wired with 4 mm² PV cable with home-run lengths on the order of 30–50 m from the array to combiner boxes or the inverter station . Strings are equipped with bypass diodes in the module junction boxes to mitigate shading effects, though shading is minimal by design .Overall, the use of high-efficiency 505 Wp modules and long strings reduces the total number of strings and combiners needed, simplifying the DC cabling and reducing losses.

5.4. Inverters and Transformer Stations

Inverter Selection: The plant employs 42 units of Riello SolarTech Sirio Central Station (SCS) 1000 inverters fig.16 each rated 1000 kVA / 1000 kW_{AC} at unity power factor. These are central inverter stations designed specifically for large-scale solar farms, integrating power conversion and a medium-voltage (MV) transformer in a single prefabricated cabin. Each SCS 1000 station can handle up to 1 MW of AC output and consists internally of two 500 kW inverter units working in parallel (two MPPT channels), coupled to a dedicated 20 kV step-up transformer . The integrated design provides a plug-and play solution: the inverters and transformer are pre-assembled in a reinforced concrete enclosure that meets utility standards (CEI 0-16 in Italy) and only needs to be placed on site and connected . This greatly reduces on-site installation time and ensures a robust, weather-proof housing for the power equipment.

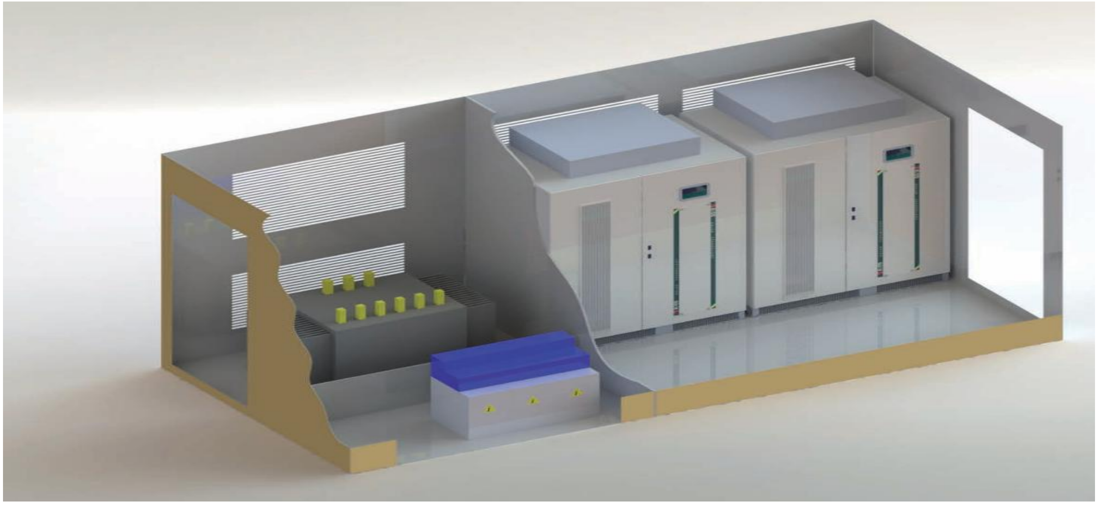

Figure 16 Riello SolarTech Sirio Central Station (SCS) 1000

Inverter Electrical Specifications: Each SCS 1000 has a maximum DC input voltage of 1000 V and an MPPT operating window from 530 V to 820 V at full power . This MPPT range aligns well with the array design – the 19-module strings produce ~636 V at nominal operating conditions, right in the middle of the inverter's optimum range. The inverter's maximum DC input current is 2 × 1180 A (two paralleled inputs of 1180 A each for the two internal MPPTs) , giving a total DC current capacity of 2360 A. In practical terms, each 1 MW inverter can accept on the order of 200–300 strings (depending on string Isc ~15.9 A) through combiner inputs. The AC output of the inverter is three-phase 50 Hz at 20 kV line-to-line, delivered directly by the integrated transformer (the low-voltage side of the transformer is connected to the inverter's output bridge, and the high-voltage side is 20 kV feeding the MV grid) . The inverter can operate at full output over a frequency range of 47.5 to 51.5 Hz to meet grid code requirements . It also supports power factor control from 0.9 lagging to 0.9 leading, allowing reactive power support as needed .Notably, the conversion efficiency of the SCS 1000 stations is very high: 97.3% peak efficiency (European weighted efficiency 96.7%) even when including internal transformer and auxiliary losses . This means only ~2.7% of DC energy is lost in inversion and transformation, which improves the plant's performance ratio. All inverters are equipped with protection and monitoring systems.

Physical Design: The inverter + transformer are housed in a heavy-duty concrete cabin (approx. 5.44 m × 2.50 m footprint, 2.55 m tall) . Each cabin weighs about

22 tons , reflecting the robust construction. The concrete enclosure provides excellent thermal inertia and protection against weather, and it is treated with waterproof coatings and quartz exterior paint for durability . Importantly, the design uses natural ventilation to cool the inverters without active air-conditioning . This “passive cooling” approach is possible due to the high efficiency of the electronics (minimal waste heat) and yields maintenance and energy benefits, The inverter is specified to operate from –20 °C to +45 °C without derating , which comfortably covers the environmental temperature range in Northern Italy

In summary, the Riello SCS 1000 inverter stations offer a secure, efficient, and grid-compliant solution for this plant. They simplify onsite construction and meet all Italian grid code requirements (CEI 0-16), including protections and remote dispatch capabilities. Their high efficiency and integrated MV output contribute to the overall performance of the PV system.

5.5. Array Layout, Mounting Structure and Row Spacing

Site Layout: The PV arrays are deployed on a flat open terrain in Trino, with minimal natural shading . The seven zones are contiguous or adjacent sub-areas that together cover the required land for ~51 MWp. The layout of each zone consists of multiple rows of PV modules on ground-mounted frames. All modules are oriented due south (azimuth 0°) to capture maximum solar irradiance, since the site is in the northern hemisphere. The modules are fixed at a tilt angle of 38° from horizontal . This tilt was chosen as it provides a good annual energy yield balance between summer and winter. At 38° tilt, the modules are angled enough to shed rain and snow, and to reduce soiling accumulation, while not being so steep as to significantly increase wind loads.

Each mounting structure holds a set of modules in a rigid frame. The modules are configured in landscape orientation . The support structure is made of galvanized steel (posts and racking rails), with pile-driven foundations to avoid concrete works. The fixed-tilt racks are designed to withstand the site’s wind speeds and snow loads, in compliance with Eurocode and Italian construction norms. The front edge height of the modules is roughly 0.5–1 m off the ground. This clearance allows vegetation maintenance and reduces shading of the lower edge.

Inter-row Spacing: A critical aspect of the layout is the distance between module rows (pitch) to avoid inter-row shading, especially in winter when the sun is low.

The design employs a row spacing that ensures little to no shading at least during the high-value solar hours. Based on the 38° tilt and the site latitude, the minimum row spacing was determined such that on December 21 (winter solstice) around solar noon, each row's shadow just reaches the foot of the next row. This criterion prevents extended shading on module rows in winter. Calculations indicate a spacing on the order 2,7m according to eq(2) . This configuration ensures that shading losses are very small – essentially zero near midday, and only a brief shading of the bottom of rows during the very early and late hours on winter days. According to the simulation results shading loss is under 1% of annual production, confirming the effectiveness of the chosen row spacing.

$$d = l * \sin(\beta) * \tan(90 - \alpha) \qquad \text{eq.2}$$

Where d :distance between strings
L:length of the panel
β: **Tilt angle** of the module
α: **Solar altitude angle** at the worst-case time (23.5 degrees)

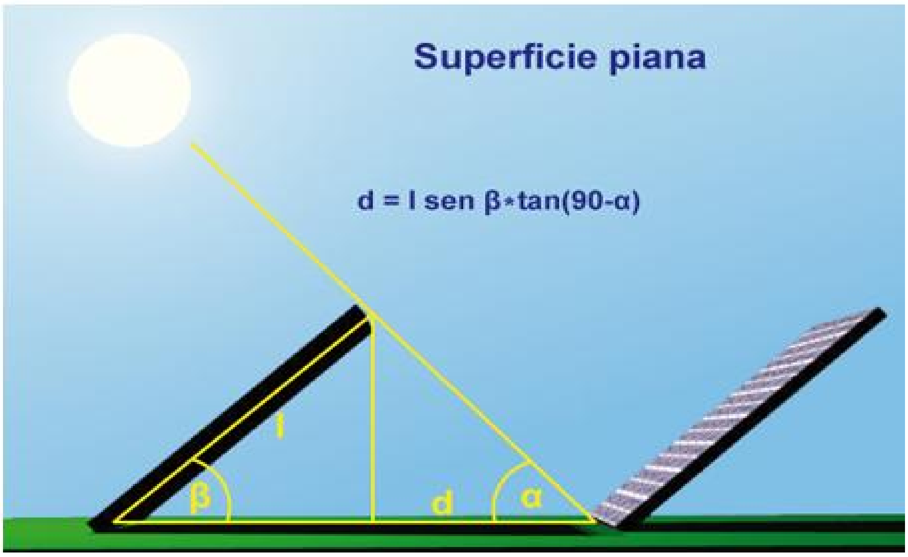

Figure 17 Minimum distance between rows

The modules are faced south and fixed – no tracking system is used – which simplifies the design and lowers maintenance. Although single-axis trackers could increase yield, the decision for fixed-tilt was likely based on economic and practical considerations (e.g. easier installation on the flat site, lower O&M costs, and avoiding moving parts given the climate). With fixed tilt, the plant achieves an annual specific yield of around 1240–1260 kWh/kWp

In summary, the array layout and mounting structure are optimized for maximum capture of solar irradiance with minimal losses. The 38° fixed tilt and south orientation are close to ideal for the latitude. The robust mounting structures secure the high-efficiency modules in place for decades, and the row spacing strategy mitigates mutual shading. The flat topography of the site further simplifies the layout no significant grading was required, and all racks sit at nearly the same elevation, which helps keep string lengths uniform and electrical design straightforward.

5.6. Electrical Design and Cable Routing

DC String Wiring: Within each zone, modules are connected in series strings (typically 19 modules per string) to achieve the required DC voltage. Each string, carrying up to ~15 A at maximum power, is routed to a combiner. The project uses solar DC cabling (UV resistant, double-insulated copper cables) of appropriate cross-section to connect modules and strings. For the module interconnections , 4 mm² copper cables are used, which keep voltage drop low while handling the string current . The average string length (distance from the farthest module in the string to the combiner) is on the order of 30–50 m. Voltage drop calculations show only a few tenths of a volt drop per string (e.g. ~0.03 V drop observed for a 4 mm² string cable of 42 m , which is negligible relative to ~600–700 V string voltage). This design ensures string wiring losses are very minor.

To manage this configuration, the system employs a DC collection architecture based on field-installed combiner boxes. In each combiner box, 16 to 24 strings are connected in parallel fig.18. Each string input is individually fused for electrical protection, and the combined output current is routed through a single, larger DC trunk cable to the inverter. These trunk cables, made of PVC-insulated copper, are typically sized at 150 mm² to 185 mm² depending on the total current and distance from the inverter station.

The electrical design connects the PV modules to the grid with high efficiency and reliability. By using short DC runs and long AC runs at 20 kV, the resistive losses are minimized. The centralized inverter stations with integrated transformers greatly simplify the medium-voltage design effectively, each zone has a few MV injection points that are easy to tie together.. All cabling and switchgear are sized according to IEC standards to handle the expected currents and fault levels. The balance-of-system (BOS) components (cables, combiners, etc.) are designed for about 15% aggregate losses from DC output to AC delivery before transformer, as allocated in the energy model. The result is an efficient transfer of power from tens of thousands of modules to a single grid connection point, with robust protections in place to handle faults or abnormal conditions.

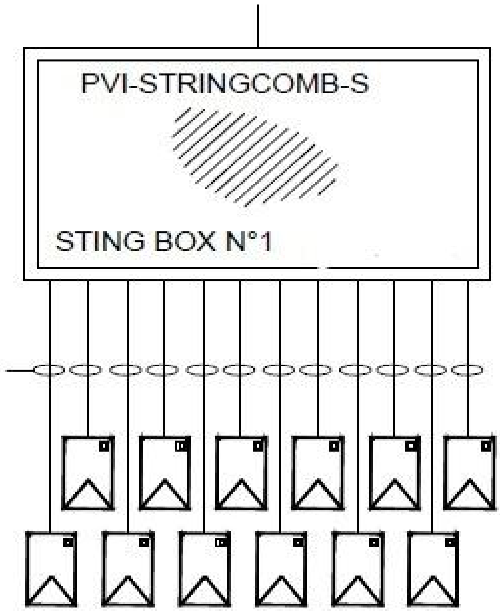

Figure 18 junction box

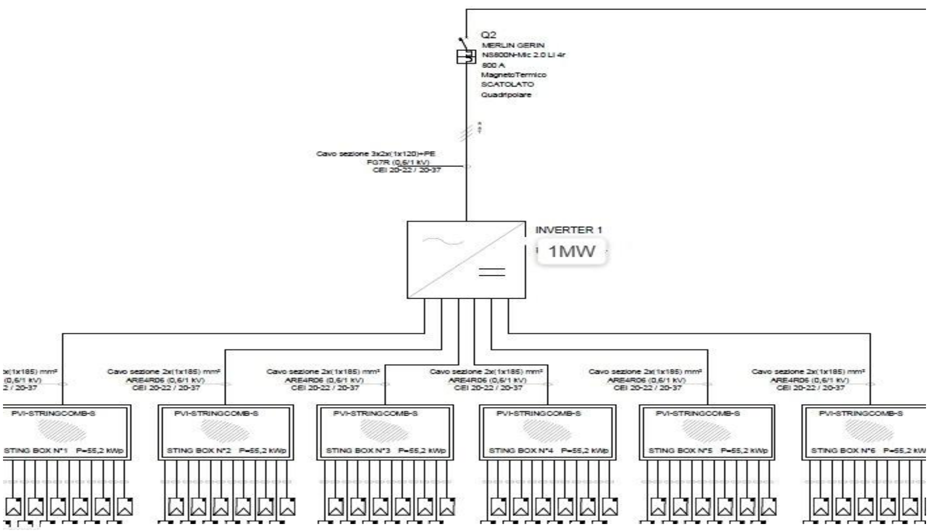

Figure 19 inverter with junction boxes

5.7. DC/AC Ratio and Inverter Clipping Strategy

One of the key design considerations was the selection of the DC/AC ratio (oversizing factor) for each zone, which determines how much PV capacity is attached per inverter. Oversizing the DC capacity relative to the inverter AC rating can increase energy production during suboptimal conditions (morning, afternoon, winter) at the cost of clipping some power during peak conditions. In this project, some zones are oversized and some are undersized. The overall DC/AC ratio of ~1.22 means that under ideal STC conditions the array could produce ~22% more power than the inverters can convert. However, such ideal conditions (1000 W/m² irradiance, 25 °C cell temperature) occur rarely; most of the time, the inverters will be operating below full capacity even with this oversizing.

Clipping behavior fig.20: When the instantaneous DC power from the PV array exceeds the inverter's AC limit (1 MW for each unit), the inverter will limit its output to 1 MW – effectively "clipping" the peaks of production. The excess DC power is not utilized so the inverter shifts the array's operating point off the maximum-power point to restrict input power). This typically occurs only around local solar noon on very clear, cool days when the array is at its maximum output. For example, in Zone 4 (DC/AC ~1.38), the 8.25 MW_p array could produce up to ~8 MW on a cold sunny midday, but the 6 MW of inverters will cap the output at 6 MW, clipping ~2 MW of potential. However, those conditions might last only an hour or two per day. Simulation results show that even a 1.3:1 ratio leads to only a few percent of annual energy being clipped , the rest of the time, the extra modules are productively increasing the energy harvest in morning/evening or under cloudy skies .

Energy Yield Impact: By oversizing to 1.3, the plant ensures that inverters operate closer to full load for more of the day. During morning and late afternoon, when irradiance is lower, the surplus DC capacity allows the inverters to still generate near 1 MW each, whereas a 1:1 system would be generating perhaps 0.8 MW at those times. Thus, the energy yield (kWh/KW_{Dc}) is increased. This is evident in the expected performance ratio (PR) and specific yield: despite some clipping, the PR remains high because losses are dominated by other factors.

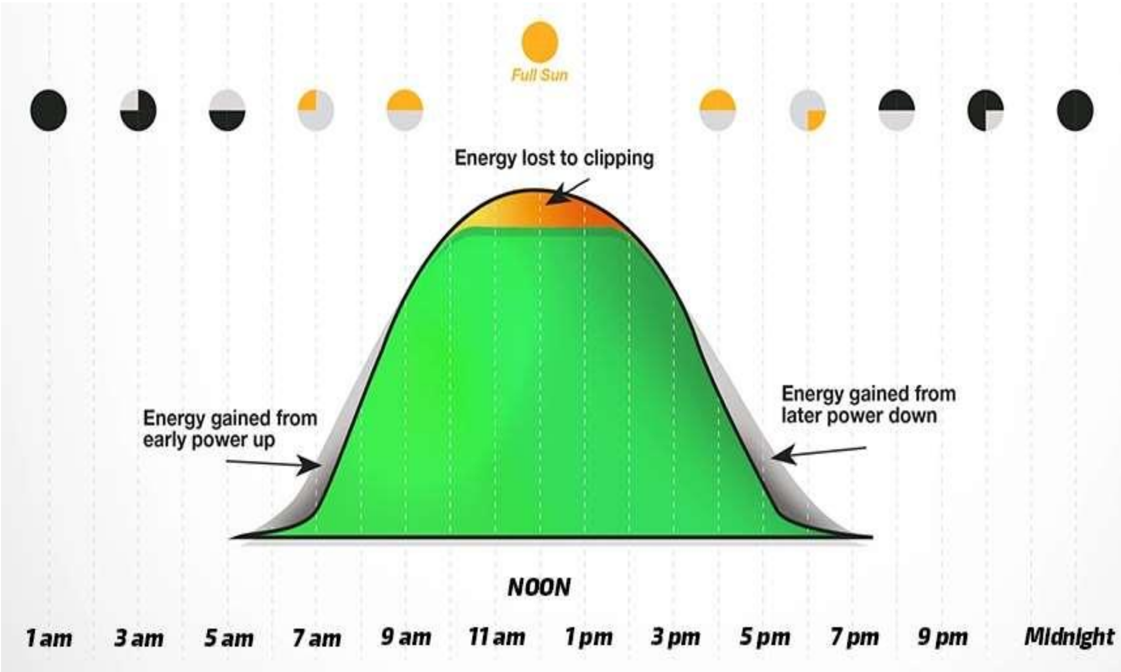

Figure 20 clipping behaviour [13]

Inverter Allocation: The design decision to use 42 inverters (42 MW AC) for a 51.3 MWp DC array was driven by this optimization logic as well as economic considerations. Adding more inverters to have a DC/AC ratio closer to 1 would reduce clipping but at significant. The marginal energy gain from eliminating the 1–2% clipping would not justify these costs under typical PPA/tariff rates. Thus, the chosen inverter count is a cost-optimal solution, aligning with industry best practices where DC/AC ratios of ~1.2–1.3 are common for utility-scale plants . Moreover, slightly higher DC loading can improve inverter operating efficiency by keeping them in a higher output range more often (inverters are often most efficient at ~50–100% load).

In conclusion, the chosen DC/AC ratios and number of inverters were justified by an energy/cost optimization. Oversizing leads to a higher capacity factor for the inverters and better economic returns up to a point of diminishing returns. The design stays within that sweet spot. Section 6 will further quantify the clipping losses and show that they are indeed limited (with graphs of inverter output vs. irradiance, etc., referenced in the analysis). By strategically oversizing, the plant maximizes use of the solar resource and ensures the inverters are not idle during non-peak hours, while accepting minimal energy shedding at the sun's peak. This approach is standard in modern PV plant design, confirming the feasibility and efficiency of the proposed system.

5.8. AC Output Calculation and Losses

To calculate the output power for each zone we should take into account different losses from DC to delivered AC as well as the inverter clipping discussed in first part the AC power output can be calculated using eq(3)

$P_{AC} = \min\left(P_{DC} \times (1 - L_{BOS}), P_{INV,rated}\right)$ eq.3

P_{DC} : is the dc power from PV array(sum of all modules)
L_{BOS} : represents the balance of the system losses including (wiring , mismatch shading ,soiling , inverter and transformer) suggested value from solarius software
$P_{INV,rated}$: represents AC rated power of the inverter .

The min function reflects for clipping :the AC output can not exceed the inverter rated power.
For Trino design, the BOS losses are estimated at 15% of the DC energy. These losses include several components: ohmic losses in DC cables (due to resistance), module mismatch losses (module IV characteristic differences and uneven irradiance), soiling losses (dirt on panels reducing light,), DC connector and combiner losses. In practice, each component is a few percent; for example, wiring losses might be on the order of 2–3% DC and another 1–2% on AC, mismatch perhaps 1–2%, soiling 3–5%, etc., summing to around 15%. This 15% BOS loss factor means that if the modules are producing 51.3 MW_DC at a given moment (STC ideal peak), about 0.85 × 51.3 = 43.6 MW_{AC} effectively reaches the output transformer.

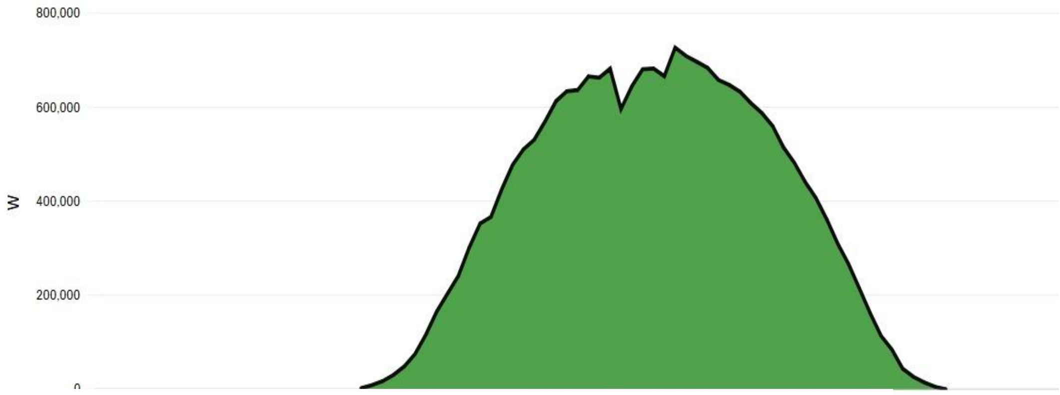

Figure 21 AC power in summer day

Figure 21 shows the AC power profile for a representative summer day. The curve follows the expected diurnal pattern of solar generation, with a maximum output of ~0.8 MW, below the inverter rated power of 1 MW. This indicates the absence of clipping losses on this day. Minor dips near noon are attributable to short-term shading or mismatch. The AC profile reflects the combined effect of BOS losses (soiling, mismatch, DC/AC ohmic, inverter and transformer efficiency).

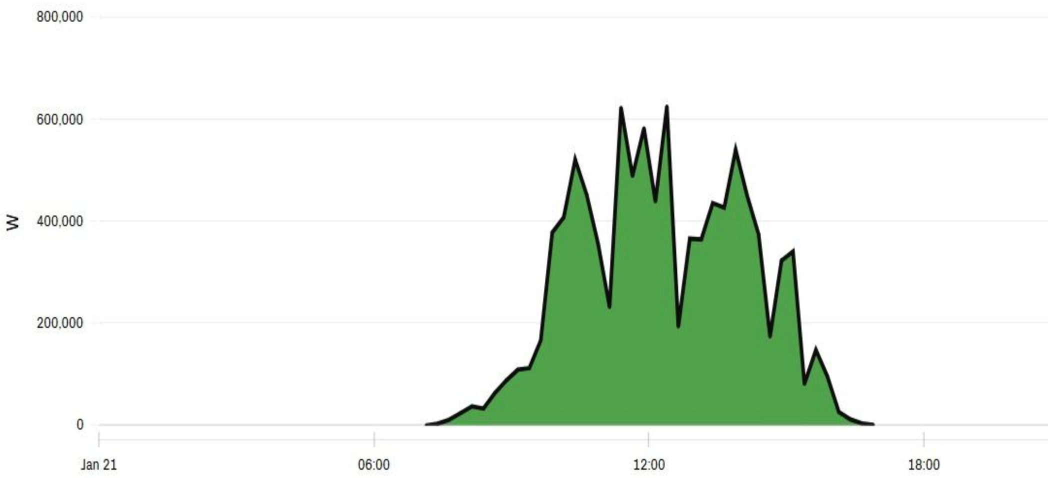

Figure 22 AC power in winter

6. Performance Analysis of the Photovoltaic System

The analysis of the performance of a photovoltaic power plant is a necessary stage in determining its technical feasibility and future value to the energy balance. Along with physical layout and component selection, one should also have knowledge of the installation's behavior under real operating conditions, in regards to solar resource variability, losses, and conversion efficiencies.

In this chapter, the results of detailed simulation calculations are presented for the 52 MWp solar power plant in Trino. The focus is placed upon estimating the yearly and monthly energy production, examining the losses' distribution along the conversion chain, and concluding performance indicators such as the specific yield and performance ratio. Particular focus is given to the effect of inverter sizing, clipping, and balance-of-system impacts since these greatly affect the overall efficiency of large PV schemes.

6.1. ZONE-1

First of all , Zone 1 fig 23 is divided to two zones due the software limits , zone 1-a with capacity of 6 211.50 kW with 12300 modules and zone 1-b with capacity of 3,019.9 kW with 5980 modules .

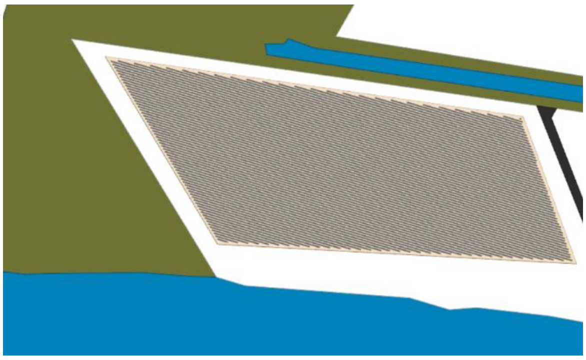

Figure 23 Area 1

Energy production 1-A: Zone 1-a is expected to produce approximately 7 781 402.76 kWh of AC energy in first year of operation This corresponds to an annual specific yield of about 1,252.7 kWh/kWp, meaning each kW of installed PV capacity generates about 1253 kWh per year. Fig.24 summarizes the simulated monthly energy production for Zone 1-a in absolute terms (kWh).

The monthly energy output shows strong seasonal variability, characteristic of Northern Italy's temperate climate. Production peaks in July is 1012012.92 KWh,

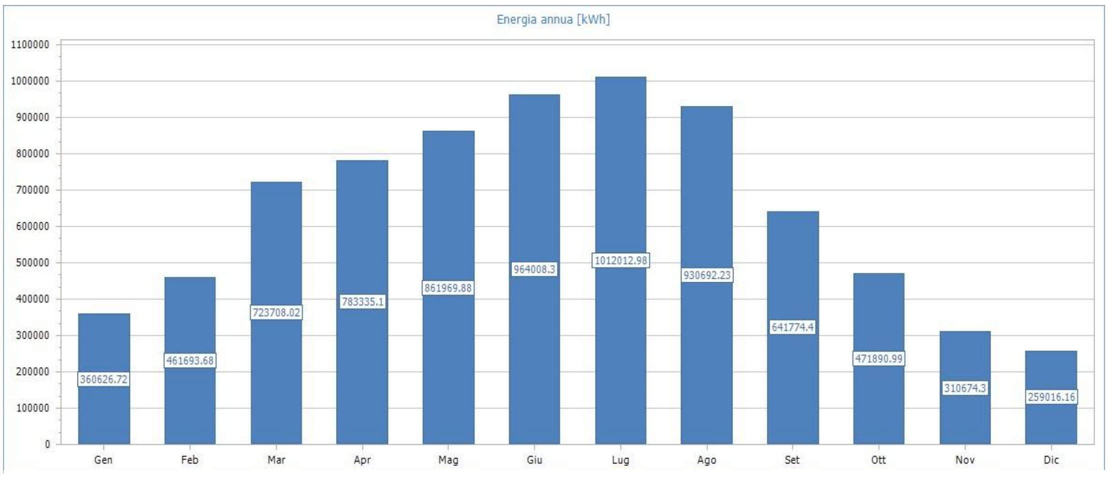

Figure 24 Monthly energy of Zone 1 -a

which is over 4 times higher than the December output 259016 KWh. The summer months (June–August) each deliver ~12–13% of the annual energy, thanks to long days and high solar irradiance. In contrast, winter months (Nov–Feb) contribute only ~5–8% each, due to shorter daylight and lower sun angles. Spring and fall provide intermediate yields. Overall, Zone 1-a s annual yield of ~7.781 GWh translates to 1,252.7 kWh per kW installed, indicating efficient energy capture for the site's latitude. This high specific yield is facilitated by favorable solar resources and optimal array orientation.

Inverter Performance: Zone 1-a is five 1 MW inverters are lightly overloaded at peak. The DC/AC ratio of ~1.24 means the array can generate about 24% more DC power than the inverters' AC rating under ideal conditions. In simulation, this led to minimal clipping – on the order of 1–2% energy loss on the very sunniest hours. The annual inverter efficiency. In summer afternoons the inverters hit their 1 MW limit, causing a clipped in output, but this lost energy is small (estimated few tens of MWh) and does not significantly reduce the yearly yield . also the shading between the rows are calculated by software by using eq.2 to ensure minimum shading in winter and summer fig 25,26 .

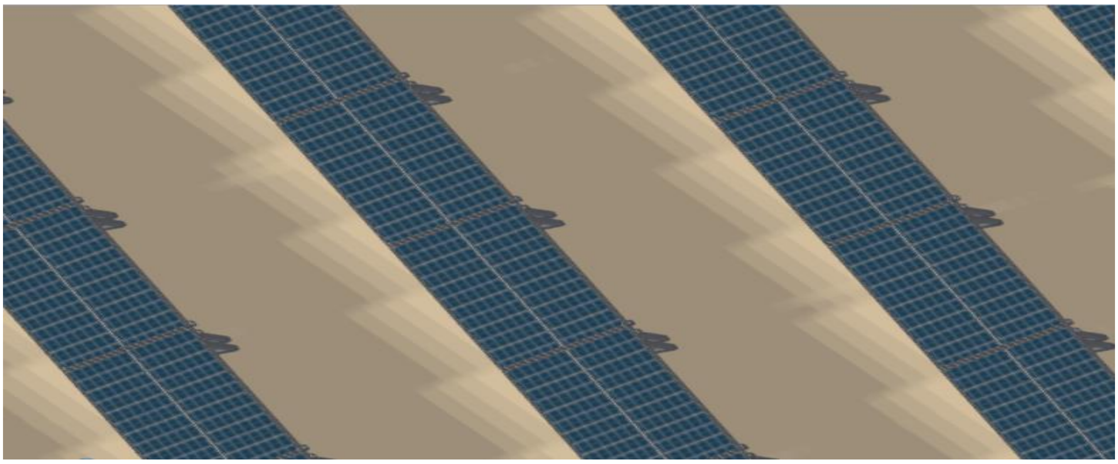

Figure 25 shading in winter between rows in 21 january

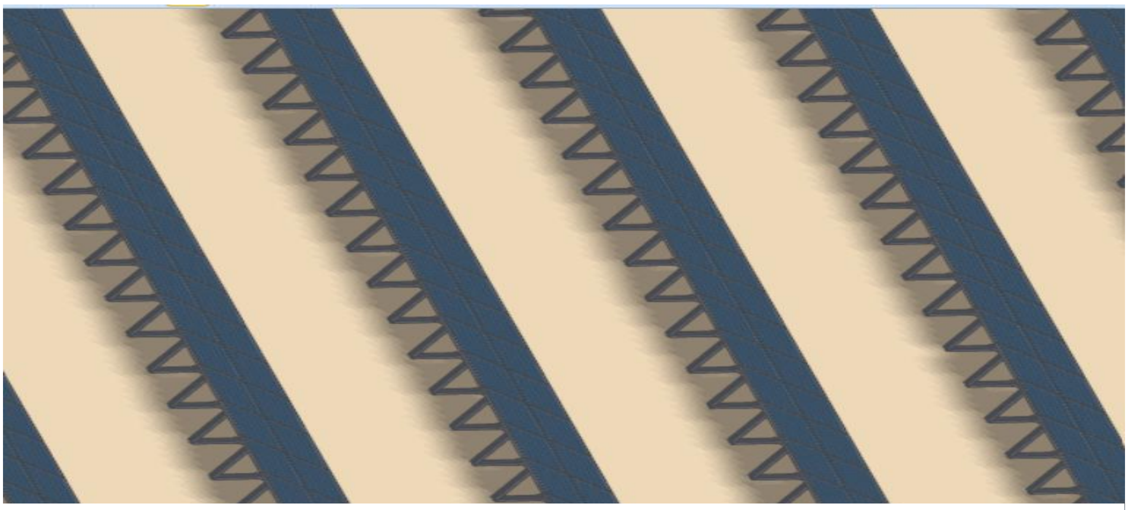

Figure 26 shading in summer in 21 june

Seasonal Effects: With little shading and identical tilt (38° south) as the rest of the plant, Zone 1-a production is driven by irradiance and temperature. The winter specific yield is lower partly due to the sun angle and shorter days, but interestingly PR in winter can be slightly higher because the modules run cooler and never reach inverter clipping. In summer, higher cell temperatures (up to ~70°C) incur a few percent power loss (temperature coefficient −0.24%/°C) , and some midday DC power is clipped, so PR dips a bit.

Energy production1-B: Zone 1-a is expected to produce approximately 3 783 151.62 kWh of AC energy in first year of operation This corresponds to an annual specific yield of about 1,252.7 kWh/kWp, meaning each kW of installed PV capacity generates about 1253 kWh per year. Fig.27 below summarizes the simulated monthly energy production for Zone 1-b in absolute terms (kWh).

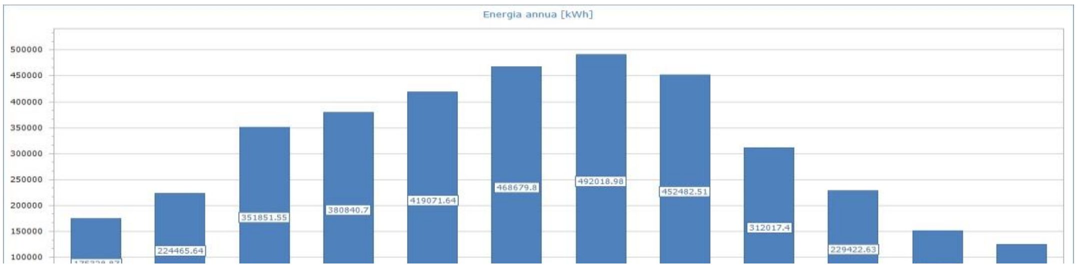

Figure 27 Monthly energy of Zone 1 -b

Inverter Performance: With a DC/AC ratio ~1.01, Zone 1B is undersized relative to its inverter capacity. The 3×1 MW inverters rarely operate at full load – in fact, peak DC power (~3.02 MW) only just reaches the 3.0 MW AC limit on the very brightest, coolest days. Thus, virtually no clipping loss occurs in Zone 1B. The inverters operate with some headroom, meaning they run slightly less efficiently at partial load (inverter efficiency is highest near rated output).

Seasonal and Shading Effects: The monthly profile is analogous to Zone 1-a. The small shading loss in Zone 1-b manifests in winter fig 28 – for example, December's specific yield (42.3 kWh/kWp) might have been ~43–44 without shading. This suggests maybe ~1–2 MWh was lost in December to horizon shading. In summer, with high sun angles, shading is negligible fig 29

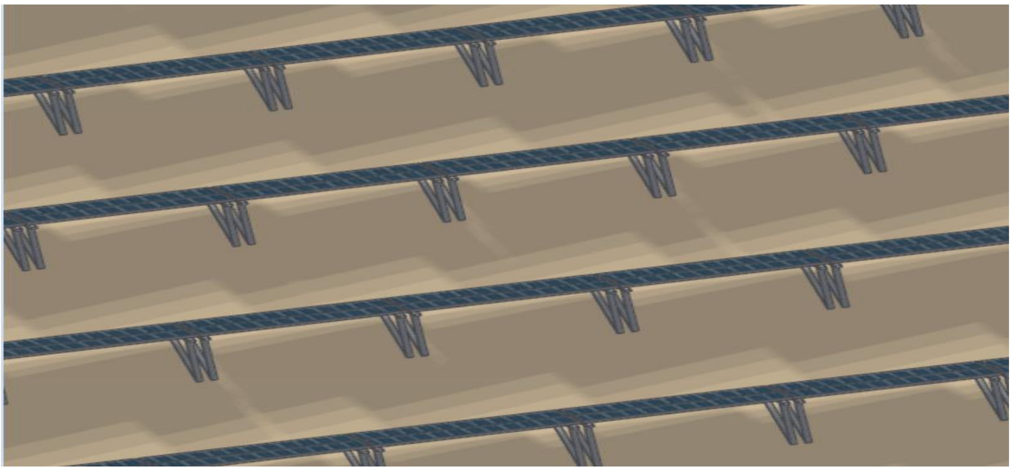

Figure 28 shading in winter

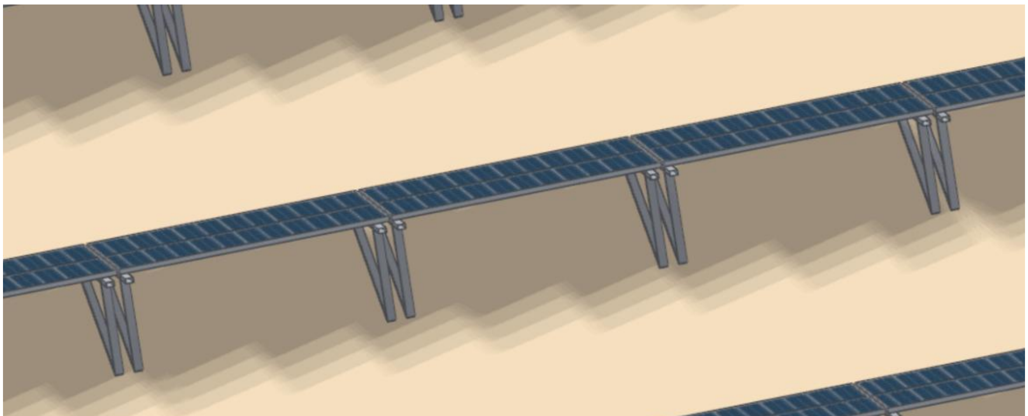

Figure 29 shading in summer

In conclusion , Zones 1-a and 1-b generate about 11.56 GWh per year (7.78 GWh from Zone 1A and 3.78 GWh from Zone 1B), with a consistent specific yield of ~1253 kWh/kWp and an overall performance ratio near 85%., the two sub-zones complement each other, delivering a stable and reliable contribution to the plant's output, and confirming that both oversizing and near-unity sizing can achieve strong technical results under the site's solar resource

6.2. Zone 2

Capacity and Production: Zone 2 fig 30,31 is a medium-size zone of the plant with 4.69 MWp DC from 9,288 modules and 5×1 MW inverters 5.0 MW_{AC} . Unlike other zones, Zone 2 DC/AC ratio is under 1.0 – it was designed with slightly less PV capacity than inverter capacity (DC/AC ≈0.94:1 in the design) . In the simulation, Zone 2 was effectively matched at 4.690 MW_{DC} .

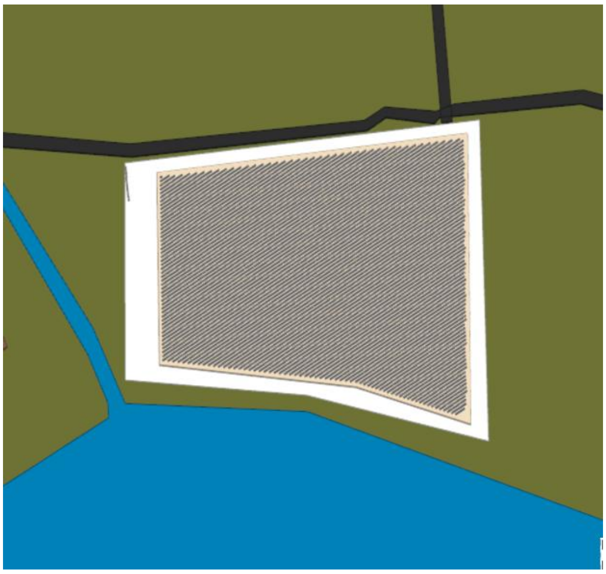

Figure 30 designed zoned in solarius software

Figure 31 zone 2 in google earth

The zone's first-year output is 5.876 GWh, which corresponds to 1252.7 kWh/kWp – again matching the other zones' specific yields, as expected given identical module orientation and an unshaded site . fig.32 summarize the monthly performance. Peak monthly output reaches 0.764 GWh in July, and the lowest 0.195 GWh in December.

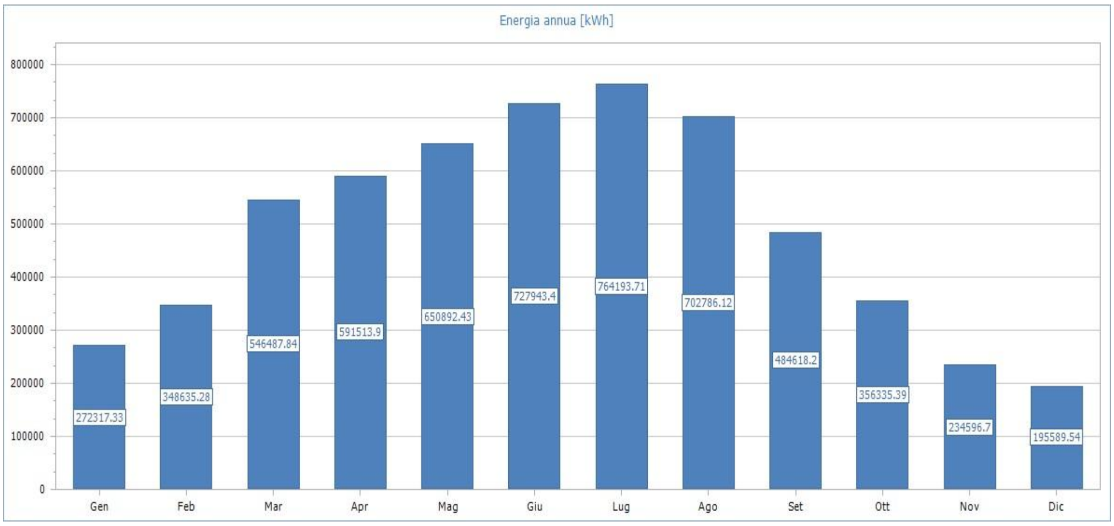

Figure 32 energy production in zone 2

Row-to-Row Shading (Zone 2): Although the simulation indicates negligible annual shading losses, the 3D layout highlights the presence of row-to-row shading during low solar elevation angles, particularly in winter months. The inter-row spacing of 2.7 m fig 33 , calculated using the solar altitude at the winter solstice, is sufficient to minimize shading at midday but still produces visible shadowing in early morning and late afternoon. The images below Fig.34,35 illustrate this effect: in summer, shading is practically absent due to the high solar altitude, while in winter elongated shadows partially cover the lower modules of adjacent rows.

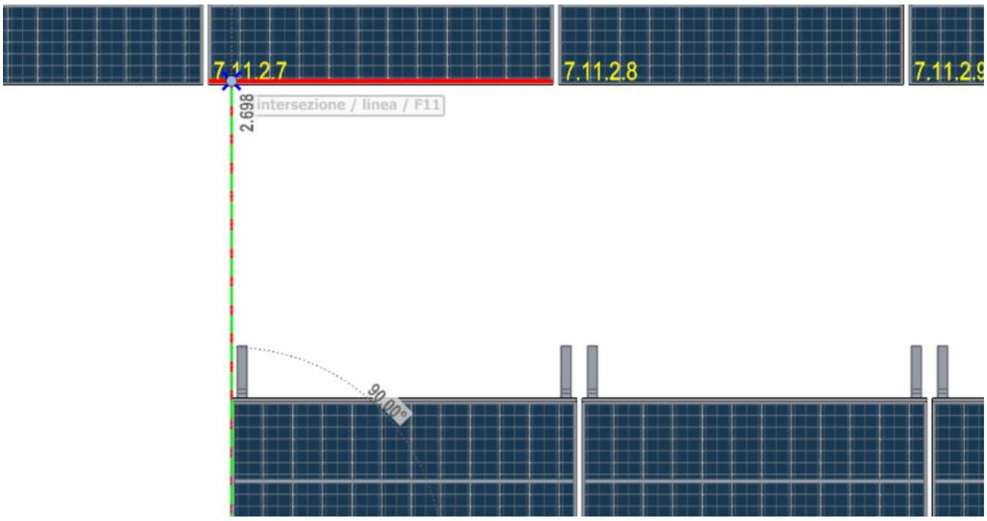

Figure 33 distance between rows

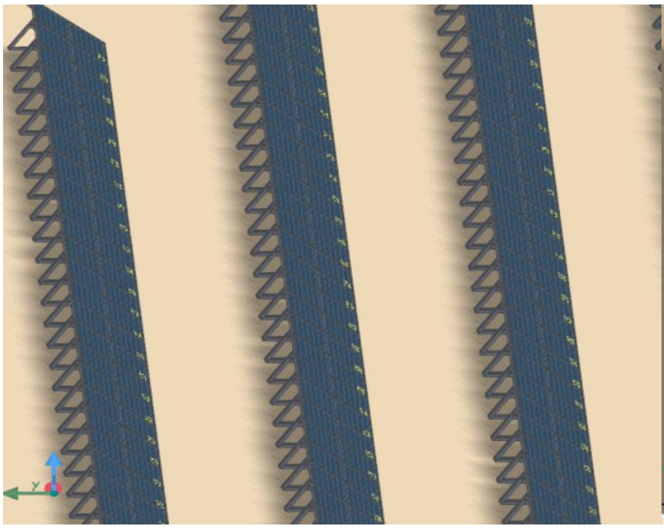

Figure 35 summer shading

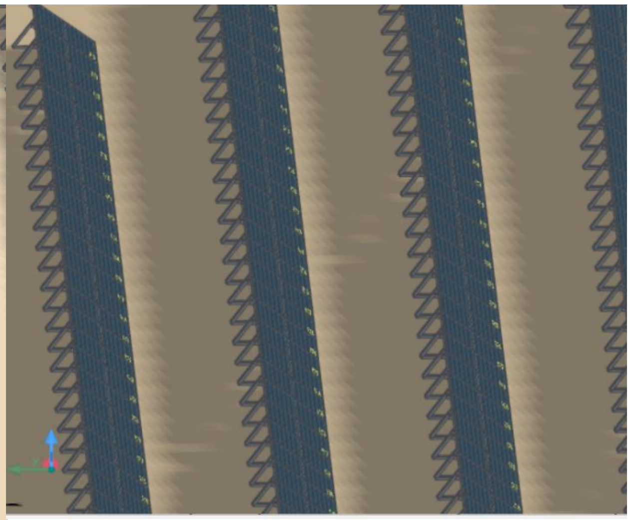

Figure 34 winter shading

Inverter Performance: Being slightly undersized in DC, Zone 2 has 5 inverters rarely operate at full capacity. The array’s maximum output (4.69 MW_{DC}) is at or below the 5 MW_{AC} available, so no inverter clipping occurs. In fact, on the very clearest, coldest days, the inverters might run 94% loaded (4.69/5 MW). This means Zone 2’s inverters have an easier job – but also implies the AC capacity is not fully utilized year-round.

6.3. Zone 3

Zone 3 fig 36,37 is one of the largest zones in the plant, with over 9.3 MWp of PV capacity installed. It is served by seven 1 MW central inverters, giving a total AC capacity of 7 MW. This represents a substantial DC oversizing (133%) – the PV array can generate well above the inverters’ limit under ideal conditions. This design is intentionally aggressive in DC/AC ratio to maximize energy yield: during most of the

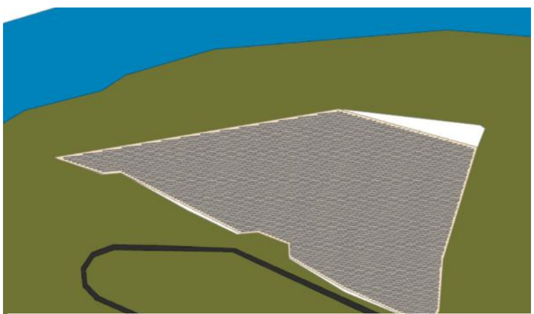

Figure 37 solarius design

Figure 36 google earth area

year, especially mornings, afternoons, and non-summer months, the full inverter capacity is not reached, so the extra PV capacity increases generation without clipping

Energy production zone 3: Zone 3 is expected to produce approximately 11.677 GWh of AC energy in first year of operation This corresponds to an annual specific yield of about 1,252.7 kWh/kWp, meaning each kW of installed PV capacity generates about 1253 kWh per year. Fig.38 below summarizes the simulated monthly energy production for Zone 3 in absolute terms (kWh).

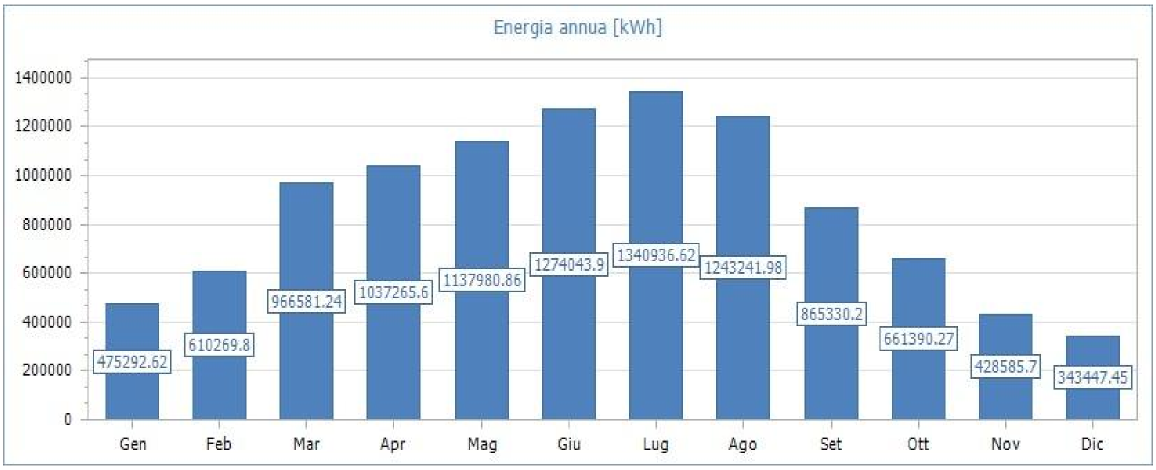

Figure 38 monthly energy production for zone 3

Inverter Performance: With a 33% DC oversize, Zone 3's inverters do experience clipping during high irradiance hours. The 7 MW_{AC} inverter capacity is significantly lower than the array's 9.32 MWp potential. On clear cool days around solar noon, the array may produce around 8–8.5 MW_{DC}, which exceeds the 7 MW AC cap. Thus, a fraction of midday DC power is clipped in spring and summer. The simulations indicate this clipping loss is small in percentage terms – on the order of 1–3% of Zone 3's annual energy . This is because such peak conditions last only a few hours per day in summer.

Row-to-Row Shading (Zone 3): The simulation output for Zone 3 confirms that shading losses are essentially negligible on an annual basis; however, the 3D model still reveals the geometric effect of inter-row shadowing under low winter sun angles. With a spacing of approximately 2.7 m between rows, defined by the critical solar altitude at the winter solstice, the layout ensures full exposure around midday, while some partial shading inevitably occurs in the early morning and late afternoon of the coldest months. As shown in the visualizations Fig.39,40 , summer operation is unaffected thanks to the high solar elevation, whereas in winter the extended shadows cast by the front rows momentarily reduce the active area of the modules behind them.

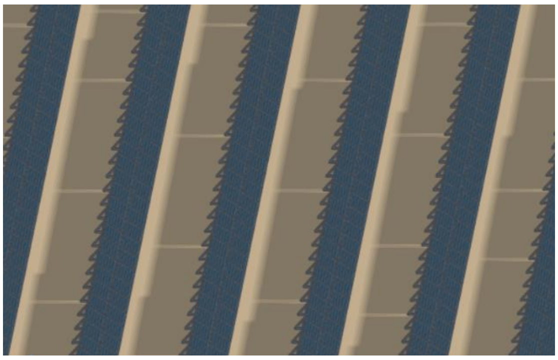

Figure 39 winter shading

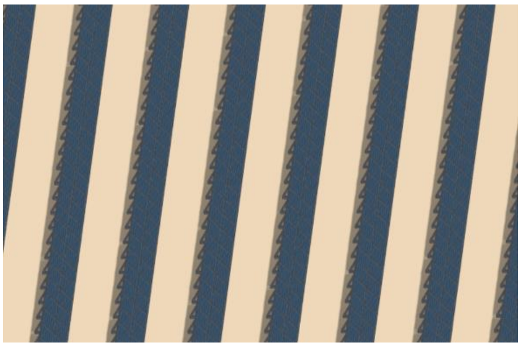

Figure 40 summer shading

6.4. ZONE 4

Capacity and Production: Zone 4 fig 41,42 is rated 8.25 MWp DC with 6x 1 MW inverters 6 MW_{AC}. It has the highest DC/AC ratio of the plant: 1.375:1 . The first-year energy yield is 10.340 GWh, below a detailed graph fig. 43 about monthly energy profuction for this zone along the first year of production .

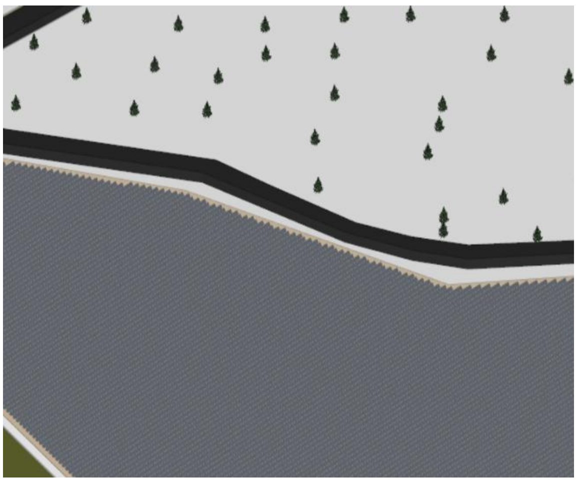

Figure 41 Solarius design

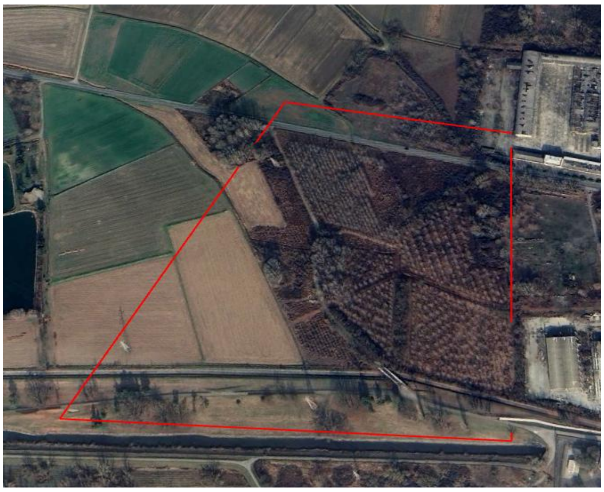

Figure 42 google earth zone

Politecnico di Torino

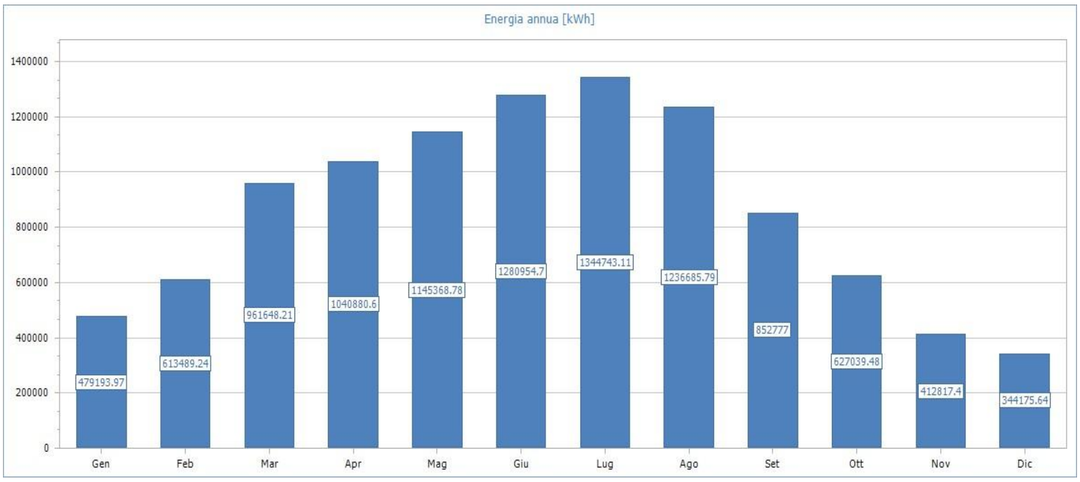

Figure 43 monthly energy production for zone 4

Clipping Losses : Due to its relatively high DC/AC ratio (~1.37), Zone 4 is among the areas of the plant most affected by inverter clipping. Under clear sky conditions in spring and summer, the PV array can deliver DC power well above the 6 MW_{AC} inverter limit, especially during midday hours. As a result, the output curve for this zone often shows a "flat-top" fig.44 profile where part of the available DC energy is curtailed. While clipping contributes only a few percent to annual energy losses, its frequency is higher in Zone 4 compared to zones with lower oversizing (e.g. Zones 1-b or 2). This design choice, however, is intentional: the oversizing increases energy harvest during mornings, evenings, and cloudy days, thereby improving overall inverter utilization

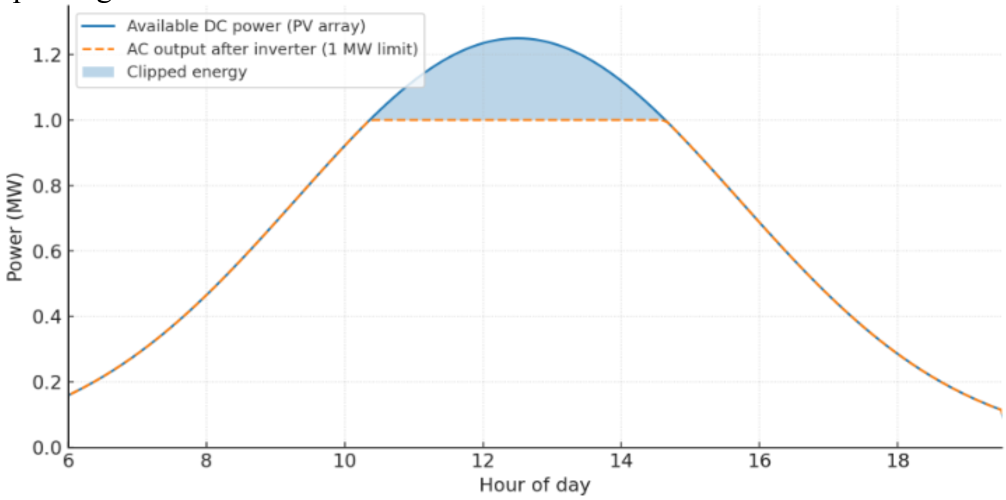

Figure 44 flat-top clipping for a 1 MW inverter

Shading Effects: Unlike the other central zones of the plant, Zone 4 is more exposed to external shading caused by surrounding vegetation FIG 42, particularly the tall trees located along the northern and western boundaries. The 3D simulations clearly show that in summer the effect of these trees is minimal due to the high solar altitude, while in winter their elongated shadows extend into the PV field and partially cover the first module rows fig.45,46 This leads to localized string-level shading during early morning and late afternoon hours, slightly reducing the overall performance of the zone.

Figure 45 Shading summer

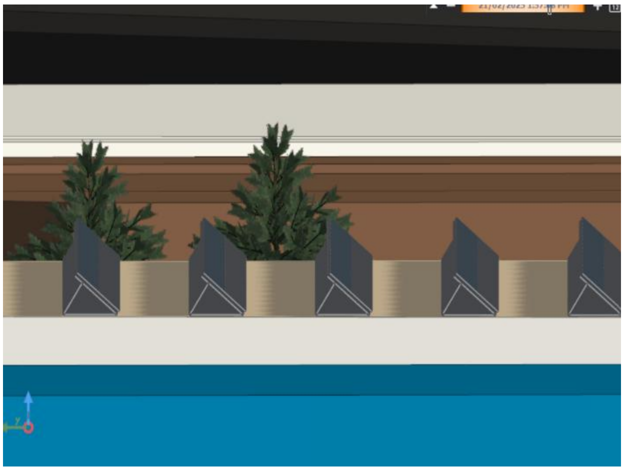

Figure 46 Shading winter

6.5. Zone 5

Zone 5 FIG 47,48 represents one of the largest sections of the photovoltaic plant, with a total installed capacity of approximately 12 MWp. Due to the high power rating, the simulation software was unable to process the entire section as a single block. For this reason, Zone 5 was divided into two sub-sections, Zone 5A and Zone 5B, each modeled separately while maintaining the same orientation, tilt, and design assumptions. This subdivision is purely a modeling requirement and does not reflect a physical separation in the real plant. The following analysis therefore presents the performance results for Zones 5A and 5B individually, followed by a discussion of their combined contribution to the overall yield of Zone 5.

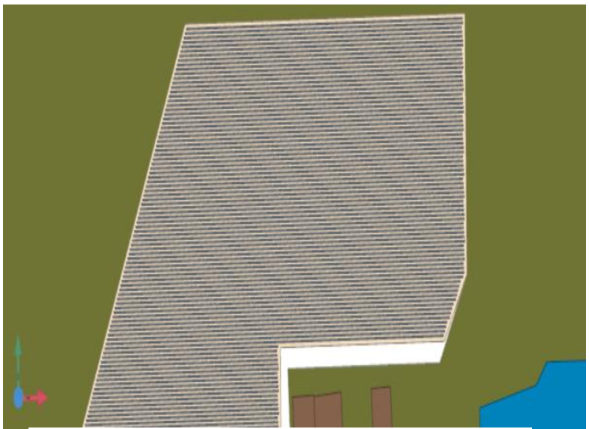
Figure 47 SOLARIUS DESIGN


Figure 48 Google earth zone

Zone 5A:

Zone 5-a is the larger portion, with about 9.27 MWp of PV with 18 354 panels . It uses seven 1 MW central inverters , giving an oversize factor 1.32:1 the performance of this zone is excellent but with smaller energy yield compared to other zones due to more shading losses due to the surrounding trees , the total energy produced in first year is around 11.56GWh, fig.49 will summarize the monthly production for this zone for first year .

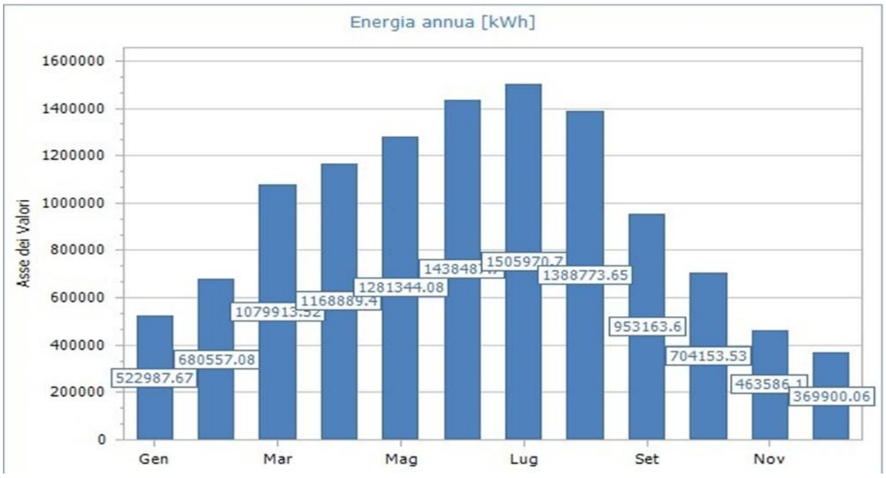

Figure 49 monthly energy production

Inverter performance : operates with a relatively high DC/AC ratio (~1.32). This configuration improves inverter utilization, as the units are able to run close to their rated output for extended periods, particularly during spring and summer. However, the oversizing also introduces clipping losses: at midday on clear days, the PV array can deliver more than 7 MW_{DC}, while the inverter output is capped at 7 MW_{AC}, resulting in flat-topped power curves. These clipped portions are small compared to the total daily generation but contribute to a few percent loss on an annual basis. In addition, module temperature effects reduce the effective DC power during hot summer afternoons, as cell temperatures rise well above 25 °C, lowering output compared to standard test conditions. The combination of clipping and thermal derating slightly lowers the performance ratio during peak summer hours, yet on a yearly basis Zone 5 still achieves a specific yield 1240–1250 kWh/kWp comparable to the other zones, confirming the robustness of the oversizing strategy.

ZONE 5B:

ZONE 5B has capacity of 2.68MW with 5319 modules with 2 inverter 2MW , the total energy generation for first year is 3.349GWh , fig.50 will represent the energy generation along the year

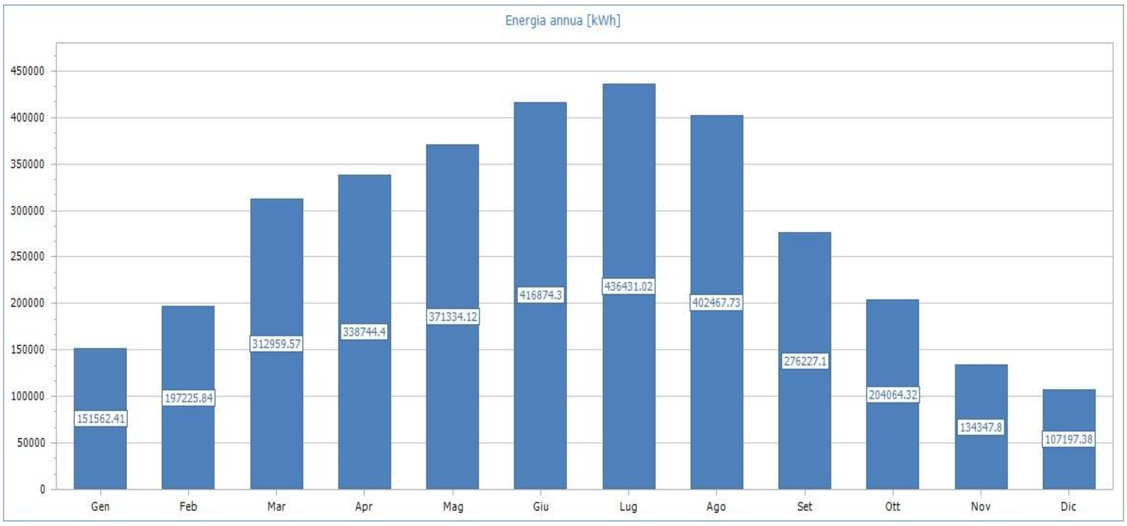

Figure 50 monthly energy generation

Row-to-Rowshading:

The layout of Zone 5 highlights the presence of row shading during periods of low solar altitude, particularly in winter. While annual losses remain modest, the 3D simulations clearly show how shadows extend from the front rows onto the modules behind them in the early morning and late afternoon. In contrast, during summer the higher solar elevation virtually eliminates this effect.

Fig.51,52 illustrate these seasonal differences, with winter shading more pronounced and summer conditions showing almost full exposure of the array.

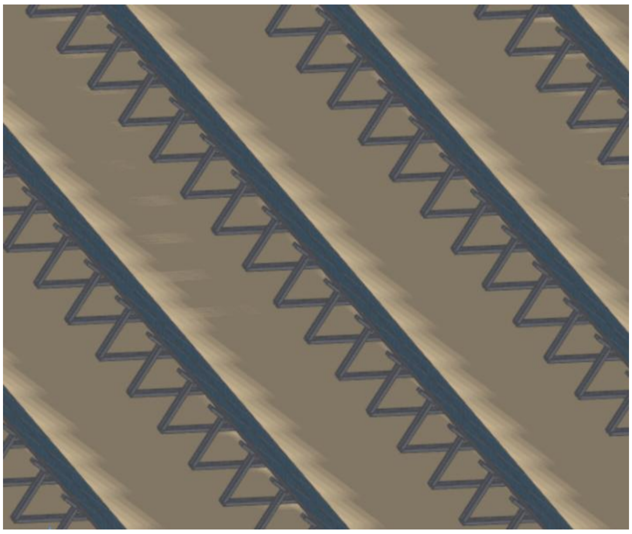

Figure 52 winter shading

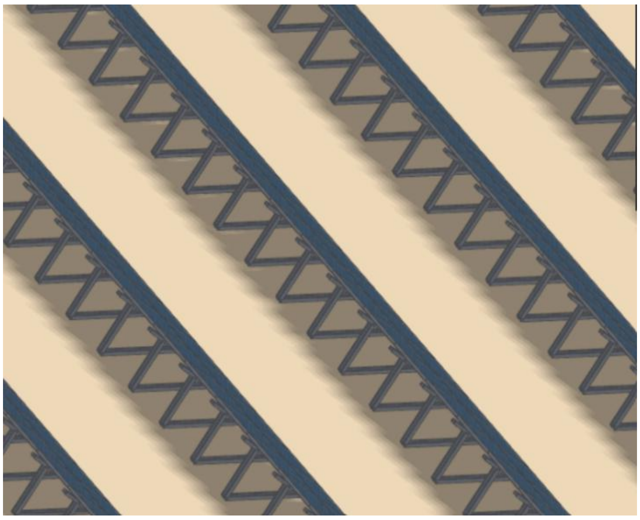

Figure 51 summer shading

6.6. Zone 6

Zone 6 fig 53,54 is the smallest zone of the plant in terms of capacity 1.94 MWp. It is served by two inverters , that gives a slight AC oversize (2 MW AC for 1.937 MW DC, DC/AC ~0.97). This is similar to Zone 2 situation where PV capacity is just below inverter capacity. In practice, Zone 6 will see no significant clipping the inverters can handle the DC power even at STC. Therefore, Zone 6 operates with virtually no inverter limiting throughout the year. Its specific yield of ~1253 kWh/kW is right in line with the best-performing zones, indicating very efficient energy conversion.

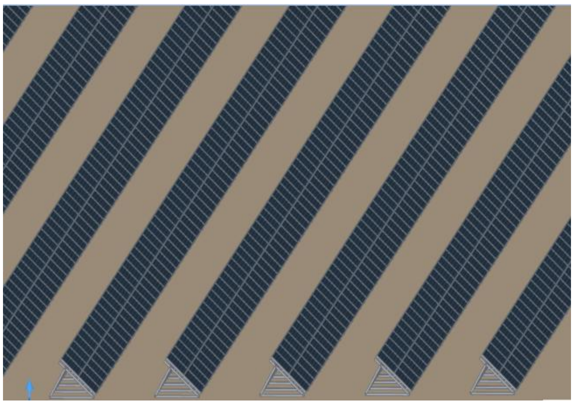

Figure 54 Solarius design

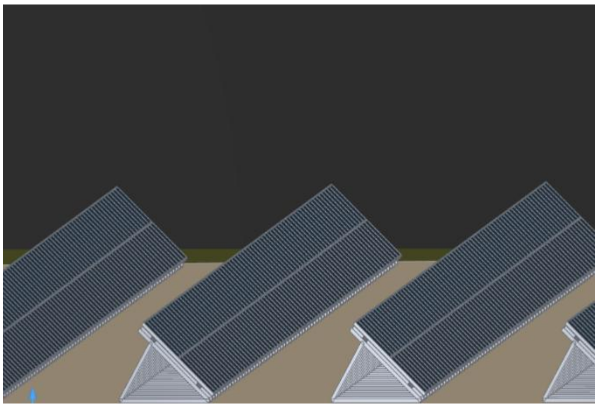

Figure 53 zoom in design

Zone 6 generates approximately 2.4 GWh per year, following the typical seasonal profile of Northern Italy: production is lowest in winter, with only around 81 MWh in December fig.55 compared to a summer peak of ~316 MWh in July, meaning the best month produces nearly five times more than the worst. The summer quarter (June–August) alone contributes about 40% of the annual yield, while winter months (December–February) account for less than 15%. Spring and autumn provide intermediate outputs, with a gradual ramp-up in March–May and a steady decline from September onward

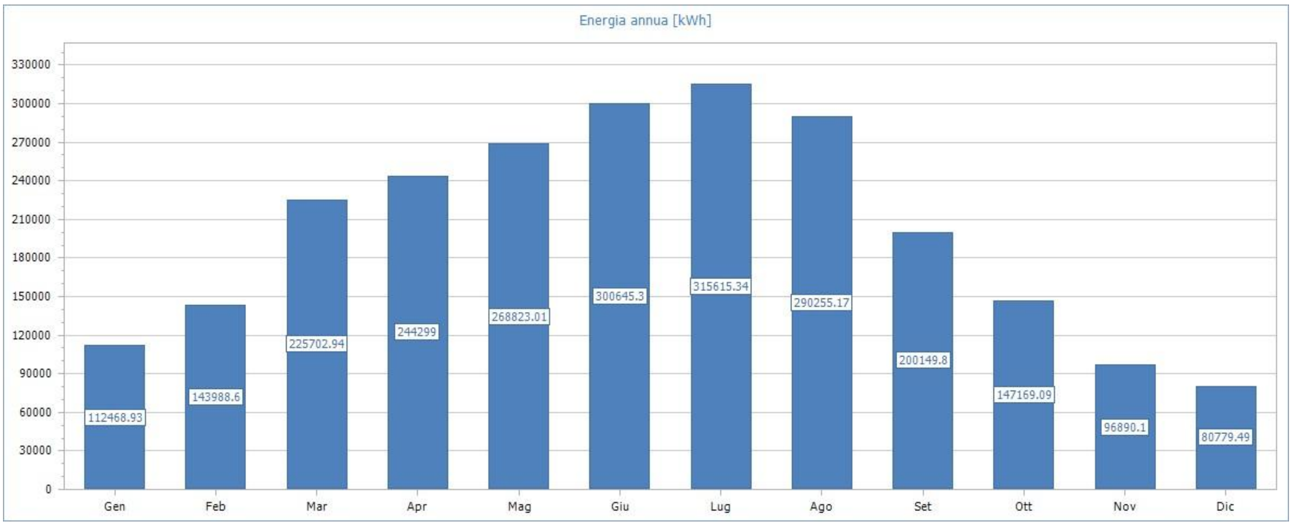

Figure 55 monthly energy production

6.7. Zone 7 :

Zone 7 fig 56,57 is the last zone, with about 5.91 MWp of PV with 11,700 modules and five 1 MW inverters. The DC/AC oversize is moderate about 1.18 , positioning Zone 7 between the highly oversized zones and the lightly oversized ones in terms of design. With nearly 7.4 GWh fig 58 annual production, Zone 7 contributes a substantial portion of the plant's output**.**

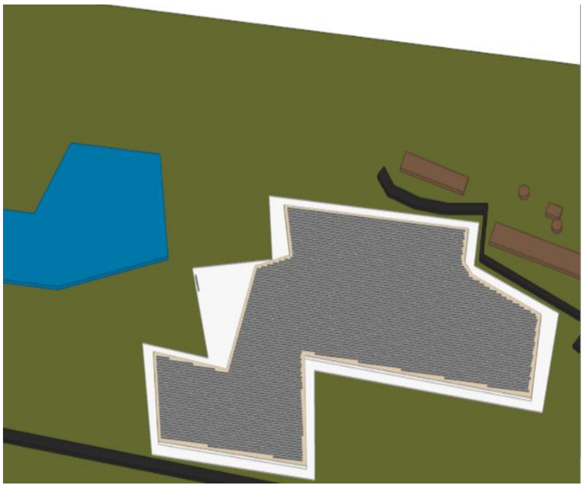

Figure 57 solarius design

Figure 56 google earth zone

Inverter loading in Zone 7 means some clipping can occur at the peak The inverters will hit their 5 MW limit during strong sun conditions for example in clear June midday, but for the majority of time they operate below limit and thus the extra panels boost energy. The result is an optimal balance and Zone 7's performance ratio remains high.

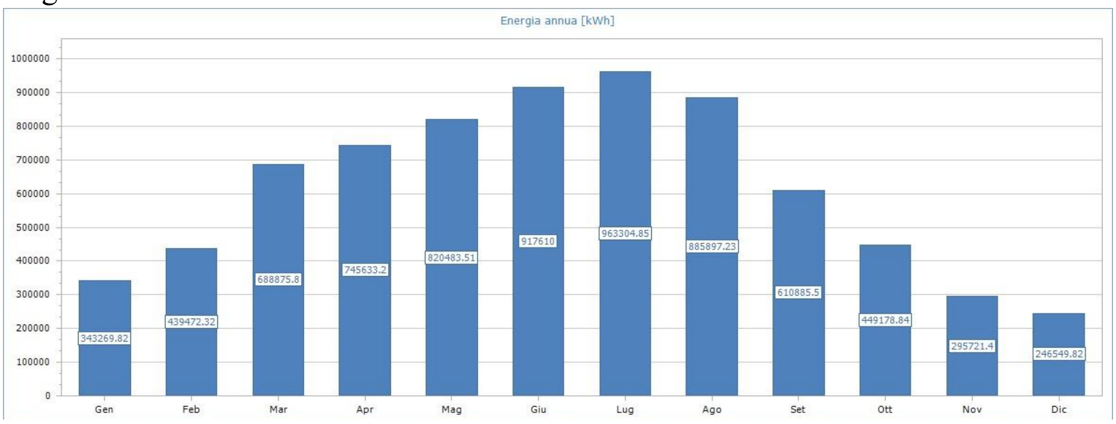

Figure 58 monthly energy generation zone 7

Also this zone like others ,row to row shading are took into considerations with distance equal to 2.7 m , because of this distance and plant is able to have minimum shading loss less than 1.5% in winter season and nearly 0.5% in summer season , fig.59,60 will show the shading losses in different seasons

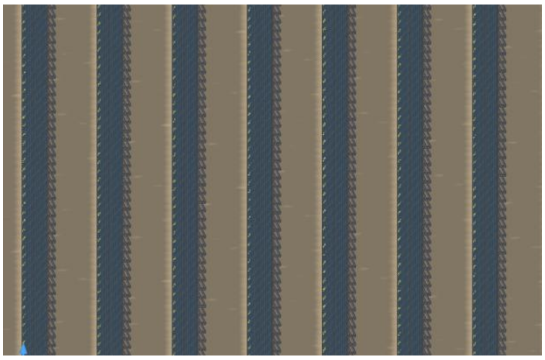

Figure 60 shading in winter

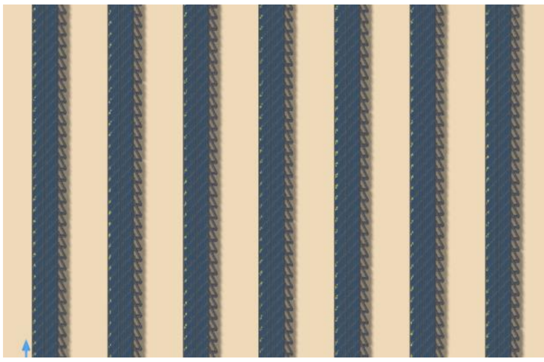

Figure 59 shading in summer

6.8. Overall Plant Performance Summary

To conclude the zone-by-zone analysis, the 52.1 MW_{DC} photovoltaic plant comprises approximately 101,587 PV modules distributed across seven zones (including sub-zones), The system is equipped with 42 inverters, providing a combined AC capacity of 42 MW_{AC} , connected to a medium-voltage (20 kV) network via multiple transformers and ultimately feeding into a common grid connection. Simulation results estimate a first-year energy production of approximately 64.2 GWh (64,198,234 kWh), accounting for all modeled losses (shading, soiling, thermal effects, wiring, and inverter efficiency). This output is equivalent to the annual electricity consumption of roughly 21,000 Italian households (assuming ~3,000 kWh per household), underlining the significant contribution of the plant to the regional energy supply.

In conclusion, the zone-by-zone performance analysis demonstrates that each section of the 52.1 MWp photovoltaic plant contributes efficiently fig 61 to the total energy yield. Minor differences in specific yield were observed due to slight shading,. The use of advanced N-type monocrystalline modules and high-efficiency central inverters yields a high specific yield around 1.25 MWh/MW, which is excellent for the geographic location. All produced energy (~64.2 GWh/year) is successfully fed into the grid, underlining the feasibility and effectiveness of the plant's design.

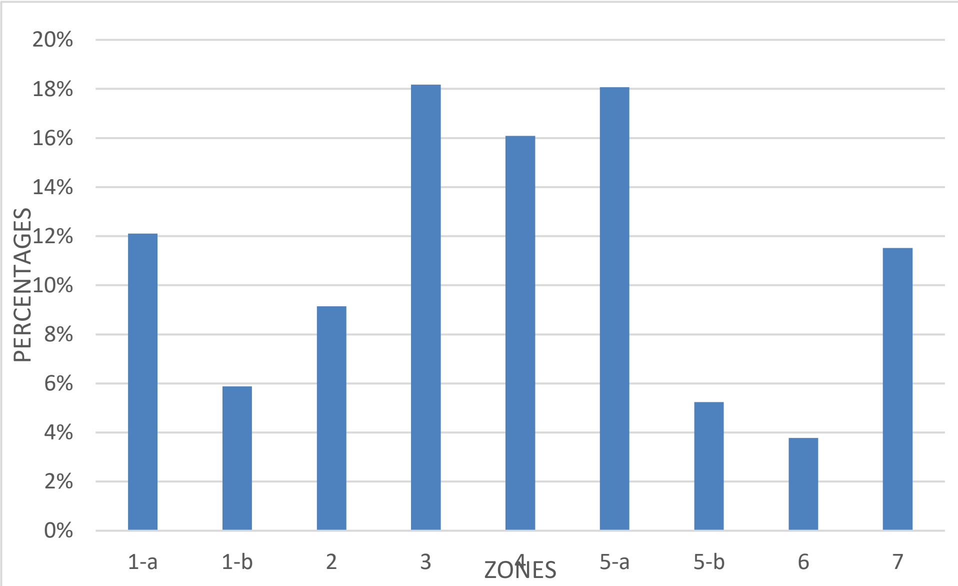

Figure 61 Percentage Contribution of Each Zone to Total Energy Production

7. Grid Connection & Energy Export

7.1. Grid Connection Layout and MV Cabling

The 52 MWp solar power plant at Trino is connected to the Italian grid by a 20 kV medium-voltage (MV) distribution system. The plant is divided into seven zones, with each delivering power into the 20 kV collection system. The zones are spaced on the site (table 2) with spacing of 120 m (Zone 1, closest to the point of connection) to 800 m (Zone 5) from the main grid coupling point. Each zone's cluster of inverters (total AC capability previously determined, being 42 MW_{AC} across the whole plant) will be served by dedicated underground MV feeder cables to the on-site substation. These radial feeders run from each zone's step-up transformer to the central 20 kV switchgear near the former Trino nuclear power plant's grid connection point. The use of one feeder per zone increases reliability – a failure or maintenance outage on one feeder will isolate only one zone, leaving the rest of the plant to continue exporting power

Column1	Column2	Column3	Column4	Column5	Column6	Column7	Column8
Zones	1	2	3	4	5	6	7
Distance to t	120	500	300	450	800	360	750

Table 2 distances between grid and zone

With the step-up transformer located at each zone and the export carried on a 20 kV medium-voltage feeder to the plant substation using 70 mm^2 aluminium cable, the electrical losses along the MV line are negligible at the zone’s nominal current of 28 A(nominal current of the transformer) The resistive loss is P_{loss} eq.2 is 0.28 kW at 28 A, which is ~0.03 % of the transferred power. The corresponding voltage drop table 3 and 4 in each section is small about 0.09% using eq.3 In practice, therefore, MV collection losses for each zone are well below 0.1 % at nominal current, and even at higher operating currents remain far below the 1 % level; the dominant AC-side losses in the collection system are the transformer efficiencies rather than the MV cable itself.

$$P_{Loss} = 3RI^2 \qquad \text{EQ.2}$$

$$\Delta V\% = \frac{\sqrt{3}I(Rcos\varphi + Xsin\varphi)}{V} \times 100 \qquad EQ.3$$

Where is , R ≈ 0.443 Ω/km and X 0.133 Ω/km[14]

zone	distance from grid(km	Rcable(Ω)	Xcable (Ω)	ΔV% at nominal current at 20 degree
zone 1	0.12	0.05316	0.01596	0.013832532
zone2	0.5	0.2215	0.0665	0.057635549
zone 3	0.3	0.1329	0.0399	0.03458133
zone 4	0.45	0.19935	0.05985	0.051871995
zone 5	0.8	0.3544	0.1064	0.092216879
zone 6	0.36	0.15948	0.04788	0.041497596
zone 7	0.75	0.33225	0.09975	0.086453324

Table3 voltage drop between each zone to grid at 20 °C

zone	distance from grid(km	Rcable(Ω)	Xcable (Ω)	ΔV% at nominal current at 90 degree
zone 1	0.12	0.06645	0.01995	0.017290665
zone2	0.5	0.276875	0.083125	0.072044437
zone 3	0.3	0.166125	0.049875	0.043226662
zone 4	0.45	0.2491875	0.0748125	0.064839993
zone 5	0.8	0.443	0.133	0.115271099
zone 6	0.36	0.19935	0.05985	0.051871995
zone 7	0.75	0.4153125	0.1246875	0.108066655

Table 4 voltage drop between each zone to grid at 90 °C

7.2. Peak Injection and Regional Demand Profile

One important aspect of grid integration is understanding how the plant's peak output coincides with or diverges from local and regional electricity demand patterns. In the case of Trino (and more broadly the Piedmont region), demand for electricity tends to peak during the day, especially on hot summer afternoons due to air-conditioning loads[15] . In fact, Italy's national peak load, which historically occurred in winter, has shifted to the summer months in recent years as space cooling usage has risen . Piedmont follows this trend, with high demand on summer weekdays during the mid-afternoon . The PV plant's peak injection 42 MW delivered around solar noon on clear summer days – thus aligns reasonably well with one of the region's busiest demand periods. The solar farm will help serve part of the midday air-conditioning and industrial load, effectively reducing the net demand that must be met by other generation sources during those hours. This alignment of solar production with peak air-conditioning-driven loads is a fortunate synergy noted in Italy's energy planning: increasing summer electricity demand coincides with peak solar PV output potential

It should be noted that while the PV output aligns with daytime peaks, it does not assist with evening demand. In Piedmont (as in most regions), after sunset the electricity demand often remains substantial early evening hours (e.g. 7–9 PM) can see a secondary peak as residential usage increases (lighting, appliances) even while solar production is zero. In winter, the peak demand typically occurs in the early evening (~6–8 PM) when heating and lighting loads are high, but solar is already offline due to the short day length. Thus, the plant has no output during the winter peak hours and cannot directly supply those. This mismatch is the classic challenge of solar power: abundant at midday, absent at night.

In summary, the 52 MWp Trino PV plant provides a valuable contribution by reliably shaving part of the midday/afternoon demand peak on sunny days. It improves the daytime load supply balance in the Piedmont region and slightly reduces the need for peaking generation or imports during those hours. Nevertheless, other resources (such as flexible generation or future storage) are required to meet the late-day and nighttime demand, as solar alone cannot cover those periods.

7.3. Curtailment Risk and Mitigation Strategies

Curtailment risk refers to the possibility that the PV plant may at times be forced to reduce its output below available capacity due to grid constraints or oversupply conditions. Several scenarios could lead to curtailment: for instance, if during a sunny low-demand day the regional grid has more generation than load especially as more PV and wind plants come online, the system operator Terna might instruct some generators to back off to maintain network stability. In normal operations, curtailments are expected to be infrequent for a 42 MW plant in this location, given the strength of the grid near the former nuclear plant. Italy's grid can generally absorb this level of solar injection by adjusting other sources like gas-fired plants can be ramped down to accommodate solar. Nonetheless, as renewable penetration grows, occasional curtailment during peak solar generation periods may become more common

Mitigation strategies are available to minimize both the likelihood and impact of curtailment. One key approach is the use of advanced inverters and plant controls ("smart inverters"). In compliance with Italian grid code CEI 0-16, the plant is equipped with a centralized Power Plant Controller (PPC) that can regulate the inverters' output in real-time based on grid conditions [16]. The PPC continuously monitors parameters at the grid connection point (voltage, frequency, etc.) and can automatically adjust active and reactive power output to support the network. For example, if grid voltage at the 20 kV bus rises too high due to heavy solar injection, the PPC can command inverters to absorb reactive power or curtail active power slightly, preventing over-voltage trips. Similarly, in an over-frequency event (indicating generation exceeds demand), the PV inverters can autonomously reduce their output to help rebalance frequency – a functionality mandated by grid codes requiring generators to contribute to system stability . All these control capabilities mean the plant can perform "active power management," throttling itself in a controlled manner when instructed, rather than simply tripping 5 6 4 offline. This not only helps avoid damaging surges but also allows for more gradual curtailment if needed, which is easier for grid operators to manage**.**

The zonal layout of the plant provides an additional mitigation aspect: the seven separate zones can, in principle, be controlled independently. If partial curtailment is required for ex reduce output by 5-10MW , the operator could shut down or limit a subset of inverters perhaps in one or two zones while the others continue at full power. This sectional control could optimize which arrays to curtail (possibly rotating between zones to equalize wear, or curtailing those with the least sunlight at that moment). It also offers operational flexibility in maintenance or abnormal conditions one zone going offline due to a fault or maintenance only removes a fraction of the plant's output, rather than the entire 42 MW. In effect, the distributed design inherently localizes any required cutbacks.

In summary, the curtailment risk for the Trino PV plant is anticipated to be low under current grid conditions, but it is addressed proactively through compliance with Italian grid regulations ensuring the plant can provide ancillary services and active power control . Smart inverters and the plant controller enable gradual and selective output reductions, and the segmented zone design localizes any necessary curtailment. Future integration of storage or advanced forecasting could further mitigate curtailment, ensuring that the plant's generation is utilized as fully as possible to the benefit of the grid.

7.4. Support to Grid Stability and Alignment with National Goals

Large-scale solar plants like this not only generate clean energy but also play a role in supporting grid stability. The Trino PV plant, by virtue of its modern inverter technology and robust connection, can enhance local grid performance in several ways. First, it can provide voltage support: the inverters are capable of reactive power control, meaning they can help regulate the voltage on the 20 kV line (absorbing or injecting vars as needed) to keep the local supply stable. This is particularly valuable in rural networks where voltage can fluctuate – the solar plant can act like a var compensator during operation. Second, as mentioned, the plant contributes to frequency stability by curtailing output in response to over-frequency or by maintaining output during under-frequency within the limits of available sunlight, helping to balance the system. The requirement to have a PPC and to abide by CEI 0-16 rules ensures the plant behaves as a grid-friendly citizen, providing services that improve overall network management . Additionally, by generating power close to where it's consumed (the Piedmont area), the plant can reduce transmission losses and congestion. Every MWh produced in Trino is a MWh that does not have to be transmitted from a distant power station or imported from another country; this eases the loading on cross-border tie-lines and long-range transmission corridors, indirectly improving stability by lowering stress on those systems.

Finally, in terms of national grid strategy, large solar plants with smart controls can be seen as building blocks of a future smart grid. They can potentially participate in ancillary service markets – for example, providing fast frequency response or voltage regulation for the TSO – and help stabilize the grid as part of a virtual power plant or other advanced schemes. While older PV installations simply injected power whenever available, new ones like Trino's are interactive and controllable resources. By supporting voltage and frequency and by being capable of curtailment on command, they align with grid operators' needs for flexibility. This ensures that as renewable penetration increases, grid reliability can be maintained or even improved. In essence, the Trino PV plant demonstrates that utility-scale solar, when properly integrated, can strengthen the grid (not weaken it) and is a cornerstone of Italy's renewable energy future. Its successful operation will serve as a model for how renewable energy projects can simultaneously deliver clean power and support the stability and sustainability goals set at both regional and national levels.

8. Economic Analysis

This chapter evaluates the economic viability of the proposed utility-scale photovoltaic (PV) plant in Trino . Building on the technical design and energy-yield assessment, translating the plant's physical performance into financial metrics that support investment decisions. Specifically, quantifying total capital requirements CAPEX, recurring operating costs OPEX, expected revenues from electricity sales in the NORD Italian market, and the resulting profitability under a transparent set of assumptions.

8.1. ASSUMPTIONS

8.1.1. WACC (Weighted average cost of capital):

It is introduced to describe the real discount rate, it accounts for several factors, such as: risk, expected return, and financial structure.

Cost of equity Ke:

$$\boldsymbol{Ke = R_f + Premium} \qquad \textbf{EQ.4}$$

Rf can be assumed as a government bond in the short term (Which can be considered a low-risk investment). By searching the web, the yield for italy's 10-year government bond was evaluated at 3.51% [17]

The premium on the other hand can be represented using the equation below:

$$premium = R_s + \beta(R_m - R_f) \qquad \text{EQ.5}$$

Rs is the stock premium given to small investors. Since a solar farm is not considered a small investment, Rs will be taken as zero.

Instead of finding Rm separately, we can find the difference between Rm and Rf which translates to EMRP (equity market risk premium). EMRP for ITALY is 7.26%[18].

Beta will be assumed as 1, which indicates that the investment moves in line with the market (instead of having a higher or lower volatility compared to the market).
Accordingly, the cost of equity Ke =10.77%

Cost of Debt Kd:

$$K_d = IRS + Spread \qquad EQ.6$$

Where IRS (Interest Rate Swap) is to ensure a fixed interest rate. This is done to reduce interest rate fluctuations and to ensure that future interest payments remain predictable and stable over the project's life. We found an IRS for a 5-year maturity in Sweden at 2.29%. [19]

On the other hand, Spread refers to an additional premium that depends on the credit risk associated with the borrower (the capability of the investor to return the capital). Assuming that the developer of the solar farm is an established company, this means that the spread will be low (we assume a value of 1.5%).

Accordingly, the cost of debt Kd = 3.79%

WACC Calculation:

Now, moving on to Debt and Equity. Solar Farms are considered a mature technology, which makes it easy for companies to raise debt capital since banks have a better understanding of the investment and can price the risk. the debt is taken as 70% while the equity is taken as 30% for most solar projects.

$$WACC = K_e \times \frac{E}{E+D} + K_d \times \frac{D}{D+E} \ = \ 5.885\% \qquad EQ.7$$

8.1.2. CAPEX of Solar farm

The Capex of a solar farm encompasses all initial costs, including the solar modules,inverter, cables along the grid, foundation construction, installation, and related expenses. These costs expressed in Euros/kW vary according to site location, article published by IRENA in 2024 called "Renewable Power Generation Costs in 2022" discusses the downfall of the installation cost of solar parks. The cause of this change was the economies of scale and the growing maturity of the sector.The Installation Cost for Italy was evaluated as 779 €/kW.

8.1.3. OPEX of Solar farm

Similar to the installation cost of solar farms, the maintenance cost (OPEX) experienced a decrease. This is due to many reasons, such as technological improvements, greater competition amongst service providers, and an increase in experience within service providers. This decrease in the price showcases the maturity and competitiveness of the market.

According to IRENA article Italy has showed an opex nearly 15 €/kW.

8.1.4. Price of Electricity:

After finding the net AEP produced by our solar farm, we need to find a price at which we're going to sell our electricity. To do so we searched for an appropriate number online. The price at which solar farms sell electricity is not constant and can vary from one to another depending on the type of agreements happening between the developers and the investors. Some companies sign a PPA to ensure stable revenue.

an average value was taken between 2024 and 2025 for electricity price , the final value is 102 Euro/MWh .

8.2. OUTCOMES

8.2.1. LCOE(Levelized Cost of Electricity)

$$LCOE = \frac{CAPEX + \sum_{k=1}^{N} \frac{OPEX_k}{(1+r)^k}}{\sum_{k=1}^{N} \frac{E_{g,k}}{(1+r)^k}} \qquad EQ.8$$

As can be seen in the equation above, the numerator represents the total lifetime cost of the investment (Capex + Opex), while the denominator represents the total lifetime energy generation. The unit of the LCOE is Euros/MWh, which represents the cost per unit of energy.

This metric is used to compare different renewable technologies, the more mature a technology, the lower its corresponding LCOE.

According to solar cell data sheet an 0.4% degradation will ocuur each year Over 30 years, the output in Year 30 is about 89.0% of the initial-year level, and the average annual production over the period is roughly 94.4% of Year-1 output.

YEAR	CAPEX	OPEX	DISCOUNT RATE	discounted oppe	energy production(GWh	depreciating productio	discounted production
0	34431800	0	1	-	-	64	
1	0	663000	0.945179584	626654.0643	64	63.744	60.24952741
2	0	663000	0.893364446	592300.6279	64	63.489024	56.71883677
3	0	663000	0.844389836	559830.4611	64	63.2350679	53.3950486
4	0	663000	0.798100034	529140.3224	64	62.98212763	50.26603819
5	0	663000	0.754347858	500132.6299	64	62.73019912	47.32039134
6	0	663000	0.712994195	472715.1511	64	62.47927833	44.54736274
7	0	663000	0.673907556	446800.7099	64	62.22936121	41.93683675
8	0	663000	0.636963664	422306.9092	64	61.98044377	39.47929056
9	0	663000	0.602045051	399155.8688	64	61.73252199	37.16575935
10	0	663000	0.569040691	377273.9781	64	61.4855919	34.9878037
11	0	663000	0.537845644	356591.6617	64	61.23964954	32.93747872
12	0	663000	0.508360722	337043.1585	64	60.99469094	31.00730511
13	0	663000	0.480492176	318566.3124	64	60.75071217	29.19024186
14	0	663000	0.454151395	301102.3747	64	60.50770933	27.47966058
15	0	663000	0.429254626	284595.8173	64	60.26567849	25.8693213
16	0	663000	0.405722709	268994.1562	64	60.02461577	24.35334973
17	0	663000	0.383480822	254247.7847	64	59.78451731	22.92621581
18	0	663000	0.362458243	240309.8154	64	59.54537924	21.58271356
19	0	663000	0.342588132	227135.9314	64	59.30719773	20.31794207
20	0	663000	0.323807308	214684.2452	64	59.06996893	19.12728762
21	0	663000	0.306056057	202915.1656	64	58.83368906	18.00640687
22	0	663000	0.289277936	191791.2718	64	58.5983543	16.95121101
23	0	663000	0.2734196	181277.1945	64	58.36396089	15.95785081
24	0	663000	0.258430623	171339.5033	64	58.13050504	15.02270266
25	0	663000	0.244263349	161946.6005	64	57.89798302	14.14235524
26	0	663000	0.230872731	153068.6205	64	57.66639109	13.31359718
27	0	663000	0.218216192	144677.3351	64	57.43572553	12.53340529
28	0	663000	0.206253489	136746.0634	64	57.20598262	11.79893352
29	0	663000	0.194946587	129249.5873	64	56.97715869	11.10750264
30	0	663000	0.184259534	122164.0712	64	56.74925006	10.45659038

Table 3 Calculation of Levelized Cost

The value of the levelized cost was calculated using the equation mentioned previously

levelized cost :	
50870.90615	Euros/GWh
50.87090615	Euros/MWh

Table 4 Value of Levelized Cost

8.2.2. Net Present Value:

The energy found in our table should be multiplied by the electricity price to find the revenue each year, which could help find the NPV. A new column was added to the already existing table which showcases the yearly revenues of the solar farm.

Taxes on corporate income are 24% in Italy [20]

The depreciation rate of the solar modules should be taken into consideration, as this will decrease tax liability. By taking the depreciation rate into consideration (assumed as 10 years), the earnings before tax will be reduced and so will the resulting taxes.

YEAR	CAPEX	OPEX	revenue	deprecation	pre tax cash flow	tax	post tax cash flow	DISCOUNT RATE	Discounted CashFlow	Cumulative
0	34431800	0						1		-34431800
1	0	663000	6501888	3443180	2395708	574969.92	5263918.08	0.938967136	4942646.085	-29489154
2	0	663000	6475880.448	3443180	2369700.448	568728.1075	5244152.34	0.881659283	4623555.591	-24865598
3	0	663000	6449976.926	3443180	2343796.926	562511.2623	5224465.664	0.827849092	4325069.155	-20540529
4	0	663000	6424177.019	3443180	2317997.019	556319.2844	5204857.734	0.777323091	4045856.102	-16494673
5	0	663000	6398480.31	3443180	2292300.31	550152.0745	5185328.236	0.729880837	3784671.71	-12710001
6	0	663000	6372886.389	3443180	2266706.389	544009.5334	5165876.856	0.685334119	3540351.663	-9169650
7	0	663000	6347394.844	3443180	2241214.844	537891.5625	5146503.281	0.643506215	3311806.846	-5857843
8	0	663000	6322005.264	3443180	2215825.264	531798.0634	5127207.201	0.604231188	3098018.496	-2759824
9	0	663000	6296717.243	3443180	2190537.243	525728.9384	5107988.305	0.567353228	2898033.652	138209.3
10	0	663000	6271530.374	0	5608530.374	1346047.29	4262483.084	0.532726036	2270735.715	2408945
11	0	663000	6246444.253	0	5583444.253	1340026.621	4243417.632	0.50021224	2122609.439	4531554.5
12	0	663000	6221458.476	0	5558458.476	1334030.034	4224428.442	0.469682854	1984141.609	6515696.1
13	0	663000	6196572.642	0	5533572.642	1328057.434	4205515.208	0.441016765	1854702.711	8370398.8
14	0	663000	6171786.351	0	5508786.351	1322108.724	4186677.627	0.414100249	1733704.246	10104103
15	0	663000	6147099.206	0	5484099.206	1316183.809	4167915.396	0.388826524	1620596.058	11724699
16	0	663000	6122510.809	0	5459510.809	1310282.594	4149228.215	0.365095328	1514863.837	13239563
17	0	663000	6098020.766	0	5435020.766	1304404.984	4130615.782	0.342812515	1416026.783	14655590
18	0	663000	6073628.683	0	5410628.683	1298550.884	4112077.799	0.321889685	1323635.428	15979225
19	0	663000	6049334.168	0	5386334.168	1292720.2	4093613.968	0.302243836	1237269.588	17216495
20	0	663000	6025136.831	0	5362136.831	1286912.84	4075223.992	0.283797029	1156536.461	18373031
21	0	663000	6001036.284	0	5338036.284	1281128.708	4056907.576	0.266476083	1081068.842	19454100
22	0	663000	5977032.139	0	5314032.139	1275367.713	4038664.426	0.250212285	1010523.454	20464623
23	0	663000	5953124.01	0	5290124.01	1269629.762	4020494.248	0.234941113	944579.392	21409203
24	0	663000	5929311.514	0	5266311.514	1263914.763	4002396.751	0.220601984	882936.6628	22292140
25	0	663000	5905594.268	0	5242594.268	1258222.624	3984371.644	0.207138013	825314.8248	23117454
26	0	663000	5881971.891	0	5218971.891	1252553.254	3966418.637	0.194495787	771451.7134	23888906
27	0	663000	5858444.004	0	5195444.004	1246906.561	3948537.443	0.182625152	721102.2501	24610008
28	0	663000	5835010.228	0	5172010.228	1241282.455	3930727.773	0.171479016	674037.33	25284046
29	0	663000	5811670.187	0	5148670.187	1235680.845	3912989.342	0.16101316	630042.7806	25914088
30	0	663000	5788423.506	0	5125423.506	1230101.641	3895321.864	0.151186066	588918.3889	26503007

Table 5 Representation of NPV

After 30 years of the investment life, the NPV of the investment is equal to 26503007 euros

8.2.3. Payback Time:

This is when the negative cash flows are equal to the positive cash flows. In our project the payback time is 8 years.

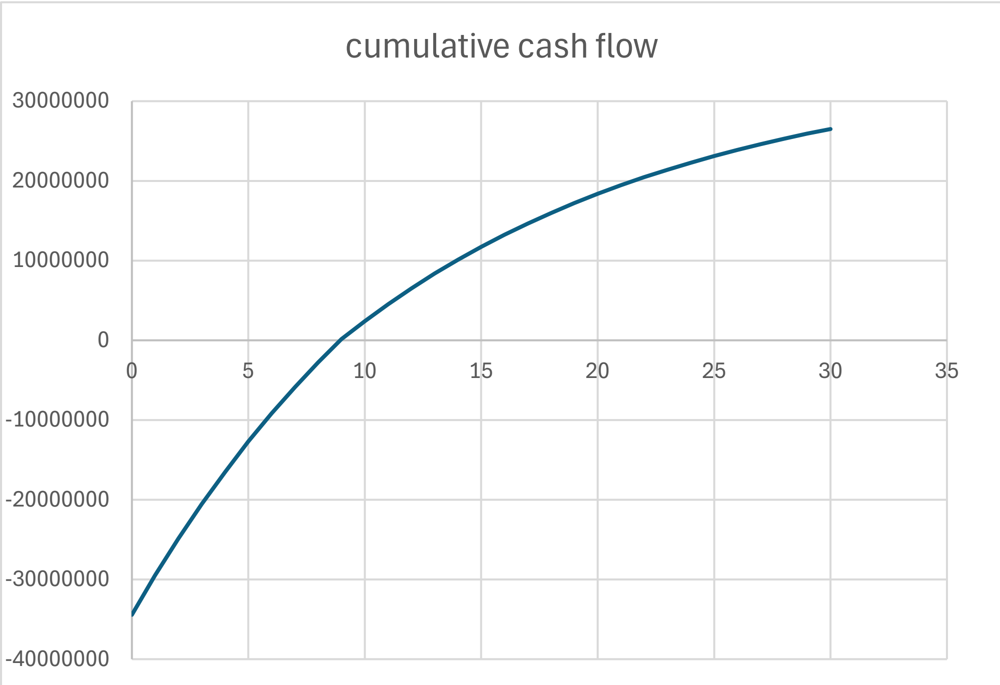

Figure 62 Payback Time

8.2.4. Internal rate of return

It is a financial metric used to evaluate the profitability of an investment. It is the rate at which the investment breaks even in terms of present value. The IRR was calculated using a function in Excel, it has a value of 13% which is greater than the discount rate used in our analysis (WACC = 5.885%)

8.3. Wholesale Price Comparison: France and Switzerland vs. Trino PV

Wholesale electricity prices in France and Switzerland have moderated in the past two years, especially compared to the extreme price spikes of 2022. According to latest data for 2024, France's average day ahead power price was about €57.7 per MWh[26] . This relatively low French price reflects the strong rebound of nuclear generation in 2024 – nuclear plants supplied nearly 70% of France's electricity that year, sharply reducing the need for expensive gas-fired power[27] . Switzerland's prices, influenced by its hydro-nuclear mix and interconnections with multiple countries, averaged roughly €75.6 per MWh in 2024[26] . By contrast, Italy's own wholesale price was much higher, averaging about €107 per MWh one of the highest in Europe [27]. Italy's higher price indicates that even with imports, domestic supply (largely gas-fired) remained the marginal price-setter for many hours.

The Trino solar PV plant's LCOE of €50.87 per MWh is notably lower than these wholesale price benchmarks. An LCOE of ~€51 means the PV plant can generate electricity at a unit cost below France's 2024 market price (~€58) and far below Switzerland's (~€75) or Italy's (~€107) . In other words, each megawatt-hour produced by the Trino PV farm is cheaper than buying that MWh from the French or Swiss grids at recent market rates. This cost advantage underscores the economic competitiveness of new solar in Italy. Even if French electricity is generally inexpensive thanks to nuclear, the PV plant approaches parity with those imports on a pure cost-per-MWh basis. The comparison is even more favorable against typical Italian spot prices, which have been twice as high as the PV's LCOE in some periods. It should be noted that wholesale prices do fluctuate hourly and seasonally, whereas LCOE is a long-term average cost. Nonetheless, on average the Trino PV plant can deliver power around 10–30% cheaper than importing the same energy, illustrating that domestic solar can be a cost effective alternative to reliance on external electricity markets.

9. Environmental and Social Impact

The 52 MWp photovoltaic plant at Trino delivers substantial environmental benefits by reducing greenhouse gas emissions and fossil fuel use. This section consolidates the data from individual zone technical reports to quantify the total annual CO_2 emissions avoided, tons of oil equivalent (TEP) saved, and primary energy savings for the entire plant. It also compares these figures to real-world equivalents like households powered, cars taken off the road, and barrels of oil displaced to contextualize the scale of the impact. The results are presented both in aggregate and broken down by zone, with visualizations for clarity.

9.1. Emissions Savings and Imported Electricity Comparison

One of the most significant benefits of the 52 MW solar plant is the reduction in carbon dioxide (CO_2) emissions achieved by generating clean electricity locally. Based on the energy yield reports from all seven zones, the plant will produce 64 GWh of electricity for the first year , which corresponds to avoiding approximately 32,014,000 kg of CO_2[17] emissions annually about 32 thousand metric tons of CO_2 for first year For perspective, this CO_2 avoidance is equivalent to eliminating approximately 5,400 passenger cars'[18] worth of emissions (assuming ~4.6 t CO_2/year per car). Over a 20-year plant lifetime, this plant can avoid 588 388 912 kg of CO2 , This figure is derived from the displaced grid emissions factor, it assumes that without this solar farm, an equivalent amount of electricity would have been generated by the conventional power mix (largely fossil-fueled) with an average emission intensity of roughly 474 g CO_2 per kWh . In the Italian context, where natural gas and coal plants historically supplied a large share of electricity, a 32 million kg CO_2/year savings is very impactful. It directly translates to a substantial contribution toward climate change mitigation over the plant's lifetime on the order of 588 388 912 kg [17]of CO2 avoided in 20 years.

Furthermore, it is instructive to compare these CO_2 savings to the emissions from imported electricity, since Italy relies heavily on imports from neighbouring countries like France and Switzerland. France's grid mix is predominantly nuclear (with low direct CO_2 output) but still includes some fossil-fueled generation. If Italy were to import an extra 64 GWh from France to cover the absence of the Trino solar plant, the associated emissions would depend on France's marginal generation sources. France's average carbon intensity in recent years has been on the order of only 20–70 g CO_2 per kWh (thanks to nuclear and renewables), 64 GWh would carry about 7,000 tons of CO_2 – an order of magnitude less than the 32,000 tons calculated with Italy's fossil-heavy factor.

Annual Fossil Fuel Savings: In terms of primary energy, the plant saves roughly 12.630×10^3 TEP [20]per year, i.e. about 12630 tonnes of oil equivalent . This means nearly 13,000 tonnes of conventional oil use can be avoided each year by using solar power instead . In practical terms, that equates to on the order of 92 thousand barrels of crude oil not burned each year using 7.3 barrels per tonne of oil[18] . The primary energy savings correspond to the same GWh/year of net generation delivered to the grid. Over 20 years, the plant would thus save ~232,128.14 TEP .

More importantly, locally produced solar energy avoids other issues associated with imports: it reduces dependence on non-renewable sources (nuclear has waste and safety considerations, and any fossil component has emissions), and it aligns with Italy's goal to increase domestic renewable generation for energy security and sustainability.

9.2. Community Benefits and Economic Value

Beyond its environmental contributions, the 52 MW solar project delivers substantial benefits to the local community and economy in rural Piedmont. The development and operation of a large-scale solar farm involve multiple stages that create jobs and business opportunities. During the construction phase, the project mobilized a significant workforce – engineers, technicians, construction labourers, electricians, truck drivers, and other skilled workers – many of whom were hired from the region. For roughly a year the typical construction timeline for a plant of this size, the site activity translated into hundreds of temporary jobs on-site. This provided an economic stimulus: local workers received wages, and spending increased in the area on lodging, food, and services to support the construction crews.

Once the solar farm became operational, it transitioned to a smaller but lasting workforce for operations and maintenance OPEX . This includes a team of technicians who monitor performance, perform regular equipment checks, and carry out maintenance tasks such as panel cleaning, inverter servicing, and vegetation management on the site. While utility-scale PV plants are highly automated and do not require many staff on a day-to-day basis, they still create a few long-term technician and site manager positions. These are often filled by local residents or involve local service contractors, thereby providing ongoing employment in the area. Moreover, ancillary roles like site security, landscaping (for ground maintenance), and periodic technical inspections generate additional economic activity for local service providers.

10. Conclusion and Recommendations

Integrate Battery Energy Storage: A key recommendation is to include a battery storage system in conjunction with the PV plant. By adding a Battery Energy Storage System (BESS), the plant can store excess daytime solar production and dispatch it during evening or night-time hours, thereby compensating for the lack of solar generation at night. This would smooth out the power supply profile and allow the project to meet demand during high-value periods after sunset. In fact, the real-world Trino solar park has already been equipped with a 25 MW/ 100 MWh lithium-ion BESS (ENEL project), which enhances grid stability and provides ancillary services. Our project can similarly benefit: storage would raise the effective capacity factor, reduce curtailment in case of grid constraints, and protect against solar price volatility (by capturing higher electricity prices in peak hours). Future expansions or phases of the project should evaluate the optimal battery size and its added economic value. Even if not implemented immediately, designing the plant with space and electrical provisions for future battery retrofitting would be prudent.

Advanced Performance Monitoring: implementing a robust performance monitoring and analytics system for the solar farm. This would involve high-precision sensors, data loggers, and possibly remote monitoring software to track the plant's output, meteorological conditions, and equipment status in real time. By continuously comparing actual performance against the PVsyst simulation estimates, the operators can identify any energy shortfalls or component issues early and take corrective action. Such monitoring would also feed back into the model: for example, if the observed performance ratio deviates from expectation, one could analyze whether soiling, shading, or outages are the cause and adjust maintenance schedules accordingly. For future research, collecting a rich dataset of the plant's performance over several years would enable analysis of degradation rates, seasonal patterns, and the 3 accuracy of yield predictions. This empirical performance verification is crucial for improving the accuracy of feasibility studies and can inform adjustments in O&M (e.g., cleaning frequency) to maximize output over the project's life.

In conclusion, the 52 MW solar PV project in Trino demonstrates strong feasibility, meeting its design and economic targets and contributing positively to Italy’s clean energy goals. The main conclusions highlight that the plant can reliably produce clean power at a cost-competitive level, and that the investment is sound under current conditions. The initial objectives of the thesis have been achieved, confirming the viability of utility-scale solar in Northern Italy. Looking forward, by implementing the recommendations above – integrating storage, monitoring performance, analyzing market trends, and staying policy-aware – the project can further enhance its performance and resilience. These steps will ensure that the Trino solar farm remains not only a successful standalone venture but also a forward looking model for sustainable power generation. Future researchers and developers can build on this work by tracking the plant’s real-world outcomes and exploring innovations (technical and regulatory) that continue to improve the outlook for large-scale solar deployment in Italy and beyond. The journey of this project from concept to conclusion thus lays a solid foundation for ongoing advancement in 4 renewable energy engineering and policy integration, steering us closer to a decarbonized energy future.

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