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Clean energy for EU islands: Hybrid PV and storage plant in Pantelleria Airport

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Hybrid PV and storage plant in Pantelleria Airport

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Summary

This report explores the feasibility and benefits of installing a solar photovoltaic (PV) plant and a Battery Energy Storage System (BESS) at Pantelleria Airport to enhance the island's energy sustainability. By utilising available land at the airport, the project aims to maximise the exploitation of unused land to reduce dependency on imported fuels, cut greenhouse gas emissions, and stabilise energy costs.

The current energy landscape of Pantelleria is predominantly dependent on imported diesel fuel, which is costly and environmentally damaging. In addition to the existing 4 MW of distributed PV installations and a small-scale BESS of 4 MW/4 MWh already in operation, the study highlights the significant untapped potential for solar energy deployment on the island. Strategic utilisation of the airport's large, underutilised surfaces is proposed for PV installations, considering the necessary regulatory and technical constraints such as the 150-meter obstacle-free zone near the runway, potential interference with communication systems, glare risks, and potential bird strike considerations.

The optimal design for the PV system incorporates a tilt angle of 20° and an azimuth of 180°, which were identified to maximise energy yield while minimising glare risks. PV modules and string inverters were selected to ensure a high power-to-weight ratio for the plant. A total of 7 MW of additional photovoltaic capacity can be installed if all three potential plots of Pantelleria Airport are fully utilised.

Battery sizing is optimised using PyPSA framework, which assesses the most economically viable storage capacity to address energy curtailment and improve grid stability. The results show a need for increasingly larger BESS sizes with the addition of PV capacity. A 5.4 MW PV installation at the airport would require a 9.8 MW/27.3 MWh BESS, and a 7.0 MW PV plant would require an 11.4 MW/33.6 MWh BESS. This analysis underscores the crucial role of energy storage in enhancing system cost-effectiveness, reducing fuel consumption, and enhancing resilience. Overall, the two scenarios enable the achievement of 46% and 50% renewable penetration, respectively.

From a financial standpoint, the report provides an estimation of the capital and operational costs associated with PV and BESS systems. The scenario with 5.4 MW PV and 9.8 MW/27.3 MWh BESS has an estimated CAPEX of € 13 million; the scenario with 7.0 MW and 11.4 MW/33.6 MWh BESS has an estimated CAPEX of € 16.6 million.

In conclusion, the integration of a PV plant and a BESS at Pantelleria Airport offers a transformative opportunity for the island's energy future. While technical and regulatory constraints present challenges. This initiative not only aligns with Pantelleria's sustainability goals but also serves as a model for renewable energy integration in small, isolated grids globally. Moving forward, it is recommended that detailed financial analysis and consultations with stakeholders (DSO and ENAC) be conducted to ensure the project's success and long-term viability.

Introduction

Pantelleria (Figure 1) is located in the Strait of Sicily, about 110 km south of Sicily and 65 km northeast of Tunisia [1]. It has an approximate area of 84.5 km², making it the fifth-largest island in Italy, as well as the largest among the smaller non-interconnected islands. The maximum length of the island is 13.7 km, while the maximum width is around 8 km. The number of inhabitants in Pantelleria is 7,665 (data as of 1 January 2019).

The island is not interconnected to the mainland, and electricity is nowadays mostly produced by diesel generators. The means of transport use petrol and diesel engines [1]. Transportation from or to the island is guaranteed by aeroplanes and ferries every day of the year and hydrofoils during summertime. The journey to Sicily takes about 50 minutes by plane, 6 hours by ferry and 3 hours by hydrofoil.

Pantelleria, an off-the-grid island without a mainland energy connection, stands to benefit greatly from a combined solar photovoltaic (PV) and energy storage system. Solar PV is a cost-effective source of electricity that can help reduce energy costs over time, while energy storage plays a crucial role in ensuring a reliable power supply. During sunny periods, surplus solar energy can be stored and then utilised during nighttime or cloudy days, thereby increasing energy availability and reducing the need for costly, polluting backup generators. Together, solar PV and storage systems can enhance Pantelleria's energy independence, supporting a stable electricity supply while decreasing both long-term costs and reliance on external energy sources.

Additional benefits of installing solar photovoltaic power and storage are:

- Job creation: Installation and maintenance of a solar PV system and storage can create local jobs and stimulate economic growth on the island;
- Environmental benefits: Solar power is a clean and renewable source of energy, which can help to preserve the natural environment of the island;
- Grid reliability: Integrating solar PV and storage with the grid provides Pantelleria with a steady power source by storing excess energy for use during periods of low sunlight. This reduces reliance on expensive peak power generation and improves overall grid stability;
- Scalability: Solar PV systems and storage can be easily scaled up or down as needed, allowing for the addition of more capacity as the island's energy needs evolve.

Pantelleria, in its Clean Energy Transition Agenda [2], has set a target of 15 MW solar PV. Currently, the island has an installed PV capacity of 4 MW and a BESS with a capacity of 4 MW/4 MWh. The island, due to its topography and extensive cultivated areas, has limited available space for the development of additional medium- to large-sized ground-based PV plants. One of the few large areas available for PV installation on the island is within the perimeter of the Pantelleria Airport.

In this context, the objective of this study is to evaluate the optimal solution for a solar and storage plant at Pantelleria Airport. The study focuses on providing sufficient information on potential solutions, estimating the installable capacity, and identifying the highest financial savings over 20 years, taking into account the specific costs of the various components. The renewable energy produced will be, in part, self-consumed at the airport and, in the majority, injected into the main grid at medium voltage (MV) and distributed to the rest of the island. The present technical study aims to utilise the indicated area optimally, ensuring the requirements and adhering to good installation practices, such as maintaining distances, minimising shading, and establishing maintenance paths.

1. Exploring the Benefits of PV and Energy Storage Integration at Pantelleria Airport

In this section, the benefits of integrating PV and energy storage at the Pantelleria Airport are discussed.

1.1. The airport

Pantelleria Airport is situated in the northern-central part of Pantelleria Island (36.8165°N 11.9689°E). The Airport serves as the main air gateway to the island, connecting it to various Italian cities and supporting tourism and local travel needs. The airport plays a vital role in connecting the island to mainland Italy. It operates seasonally with higher traffic in the summer months, attracting tourists drawn to Pantelleria's natural beauty. The airport is equipped to handle regional and national flights, making it suitable for the island's needs. The facility features two runways, runway 03/21 and 08/26, which can be seen in Figure 2. Both runways are asphalt paved.

Figure 1: Pantelleria Airport [4]

Runway 03/21:

- Measures approximately 1,220 meters in length and 30 meters in width.
- The runway is oriented approximately 30° from magnetic north when approached from one end. Conversely, the opposite end, numbered 21, is oriented 210°, which is directly 180° opposite.
- The runway cannot be used for landings from the southern approach (210°) due to the presence of a mountain obstructing the descent path.

Runway 08/26:

- Measures approximately 1,675 meters in length and 45 meters in width.
- The runway is oriented approximately 80° from magnetic north. The other end corresponds to an orientation of 260°.
- Runway 08/26 is the longest and widest runway of the two; the most aeroplanes land here.

Figure 2: Satellite picture of Pantelleria Airport

1.2. The potential of a PV plant in the airport

A PV plant at Pantelleria Airport would offer significant potential for sustainable energy production. The island offers limited options for large-scale PV installations due to its geographic constraints and land availability. The large open areas surrounding the airport, often unused for other human activities due to aviation safety regulations, make them ideal sites for PV installations. This initiative aligns with Pantelleria's broader goals to enhance renewable energy usage, reflecting global trends in airport sustainability. The plant could provide renewable energy directly to the airport and the whole island, reducing dependency on diesel generators and cutting greenhouse gas emissions.

PV installations in airports have become a practical solution for integrating renewable energy, as demonstrated by various international projects:

- Groningen Airport, Netherlands: A landmark 21.9 MW solar PV plant, commissioned in 2020, was built between the runway (at a distance of 150m) and taxiway, spanning 20 hectares. It also makes the airport self-sufficient energy-wise [5].
- Athens International Airport, Greece: A 16 MW PV plant located 180m from its runway serves as a pioneering example in the Mediterranean region [6].
- Rome Fiumicino Airport, Italy: Planned as part of the airport's ongoing sustainability initiatives, a solar PV plant of 22 MW is expected to become operational in the near future. It will be built 150m from the runway [7].

These examples illustrate how airports can use underutilised land within their boundaries, such as areas between runways or near taxiways, to support renewable energy production.

Figure 3: Netherlands - Groningen Airport, 21.9 MW installed capacity, between runway and taxiway [5]

Figure 4: Greece - Athens International Airport, 16 MW installed capacity next to runway [6]

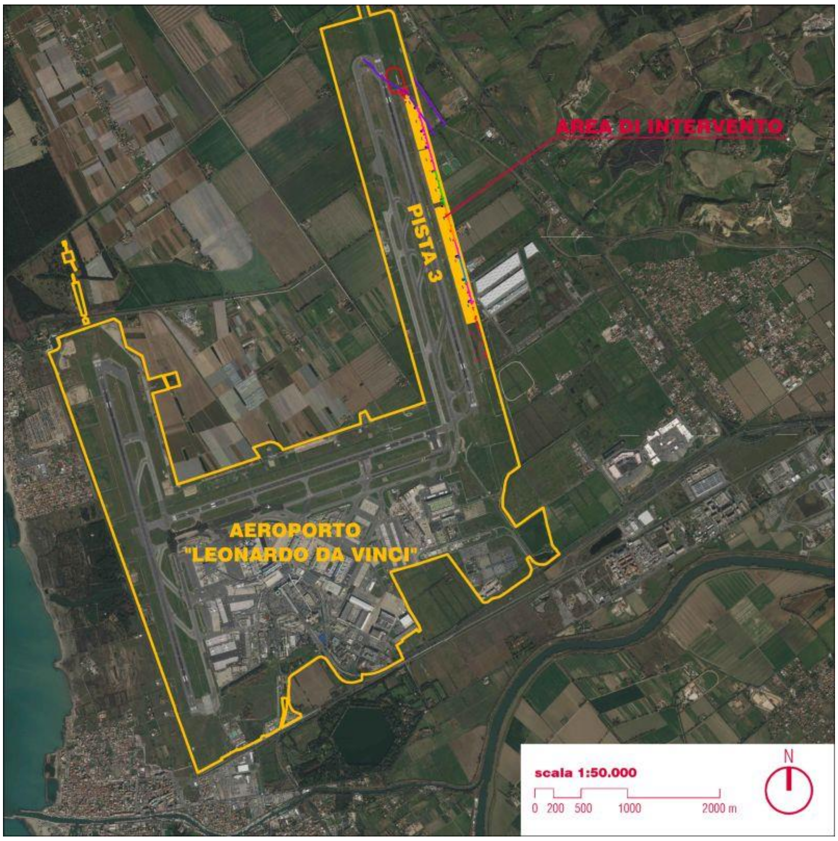

Figure 5: Italy - Rome Fiumicino Airport, 22 MW installed 150m from the runway [7]

1.3. The need for storage in the airport

A Battery Energy Storage System (BESS) at Pantelleria Airport is essential for managing the island's solar energy production and ensuring a balanced energy system. It enables better integration of renewable energy by mitigating curtailment, ensuring that surplus solar energy is stored and consumed during peak hours. This approach maximises the island's renewable energy potential while contributing to a sustainable and resilient energy infrastructure. The storage system can also support peak shaving, thereby reducing strain on generators during periods of high demand.

2. Constraints for the PV Plant

Ground-mounted PV plants at airports are subject to several constraints imposed by regulations and site-specific considerations. These constraints ensure safety, efficiency, and compatibility with airport operations. This section delves into the specific rules and regulations that impose these limitations. Key constraints include compliance with aviation safety standards, such as minimising glare to avoid visual disruption for pilots and control tower operators, and adherence to setback distances to prevent interference with radar and navigational systems.

2.1. Regulatory constraints

The potential location for PV installation is constrained by different regulations and arrangements outlined by ICAO (International Civil Aviation Organization), ENAC (National Civil Authority), the Italian government and Pantelleria Airport. These rules ensure the safety and operational requirements of nearby aviation infrastructure, restricting the placement of solar panels within specific zones or areas. Additionally, guidelines exist from ICAO, ENAC, and NREL (National Renewable Energy Laboratory) for projects involving the installation of photovoltaic systems within airport grounds. The most important ones are listed below:

Regulations and guidelines for Pantelleria Airport:

- Gazzetta Ufficiale della Repubblica Italiana - Decree 7 September 245/2016: change of status of Pantelleria airport from military to civilian in 2016. This enables commercial activities to take place at the airport [8].
- Gazzetta Ufficiale della Repubblica Italiana – Gruppo di Lavoro di Vertice, Aeroporto di Pantelleria 19/10/2016: Clarification of the various zones, the military and civil zones, highlighting their respective boundaries and regulations. These zones clearly indicate where PV installations cannot be placed, as shown in Figures 6 and 7 in Section 2.3 [9].

Regulations and guidelines for the design of airports:

- ICAO - Annex 14 Volume 1 Aerodrome Desing and Operations: detailed standards and recommendations for aerodrome design, operations, and safety. This standard specifies the dimensions of clearance zones where no obstacles are permitted. The primary consideration for installing the PV plant is the restriction that prohibits any obstacles within 150 meters of the runway. This is illustrated in Figure 7 in section 2.3 [10].

Regulations and guidelines for PV in airports:

- Gazzetta Ufficiale della Repubblica Italiana - Legislative Decree 199/2021, Art. 20: Airport areas available to airport management companies to place renewables, subject to technical checks by ENAC [11].
- ENAC - Guidelines 2022/02 APT Ed.1 del 26/04/2022: Guidelines for photovoltaic systems in the airport surroundings. These guidelines further address glare, as discussed in Section 2.4 [12].
- NREL - Siting Solar Photovoltaics at Airports: Guidelines for photovoltaic systems in the airport surroundings. These guidelines further address interference with communication systems and bird strikes, these are further discussed in Sections 2.2 and 2.5 [13].

The two key points that restrict the potential area for PV derived from this are listed below and shown in Figure 7 in Section 2.3:

- A minimum distance of 150 meters from the runway has been applied. This is also clearly visible in the other existing PV plants at airports, such as those at Groningen Airport in the Netherlands and Athens International Airport in Greece.
- No development or activity is permitted in the military zone.

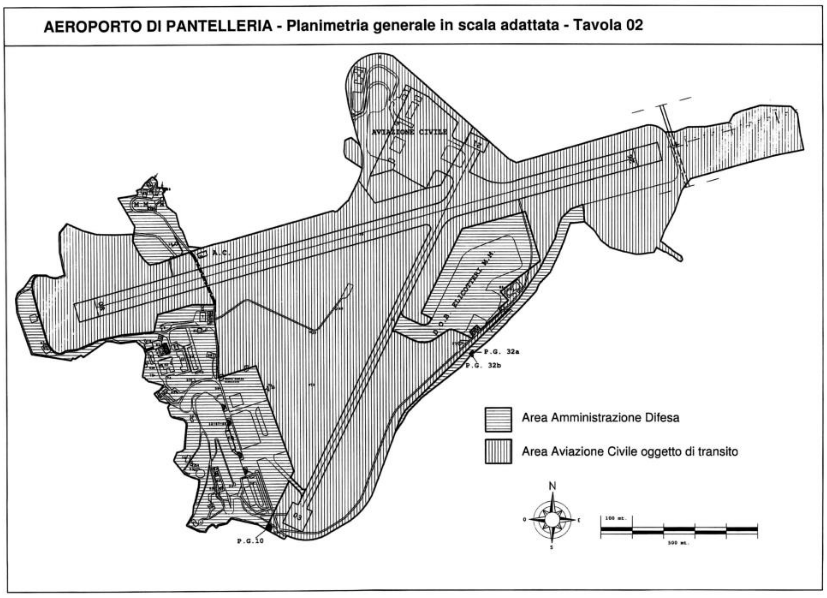

Figure 6: Military and civil zones Pantelleria Airport [9]

2.2. Interference to communication systems

Solar PV systems can pose potential interference risks to radar, NAVAIDs (navigation aids), and other communication, navigation, and surveillance (CNS) equipment at airports if not properly sited and designed. This interference occurs when objects are positioned too close to sensitive equipment, such as radar antennas, disrupting the transmission of signals between the antenna and the receiver, which can be either an aircraft or a remote monitoring location.

Metal components in PV racking systems can reflect signals, thereby exacerbating this interference. However, because solar PV systems are typically low-profile, the risk of interference is generally minimised.

The heat generated by solar panels also poses a potential interference risk, especially to infrared communications. During periods of full sunlight, PV modules can reach temperatures of approximately 50°C. This heat can be retained into the early part of dusk, potentially affecting infrared communications between the aircraft and CNS equipment. To minimise this risk, a safe radial distance of 45.72 meters (150 feet) should be maintained between PV modules and sensitive CNS equipment, like communication towers and control rooms. In some instances, greater setbacks may be necessary, depending on the specific airport and local regulations [14] [15].

While some past solar installations have required greater setbacks to prevent interference, modern solar PV technologies, including advanced low-profile racking systems and alternative materials, can help manage these challenges. A distance of 75 meters (~250 feet) from the CNS equipment has been specified, particularly for the VHF omnidirectional radio range (VOR). This is illustrated in Figure 7 in section 2.3.

Existing roads leading to radars must also be avoided. These pathways need to remain unobstructed to ensure continued access and functionality of the radar infrastructure.

2.3. Potential surface for PV

The airport's infrastructure, including roads and existing buildings, does not offer available space for PV. Combining the excluded areas mentioned in sections 2.1 and 2.2 results in the map of Figure 7.

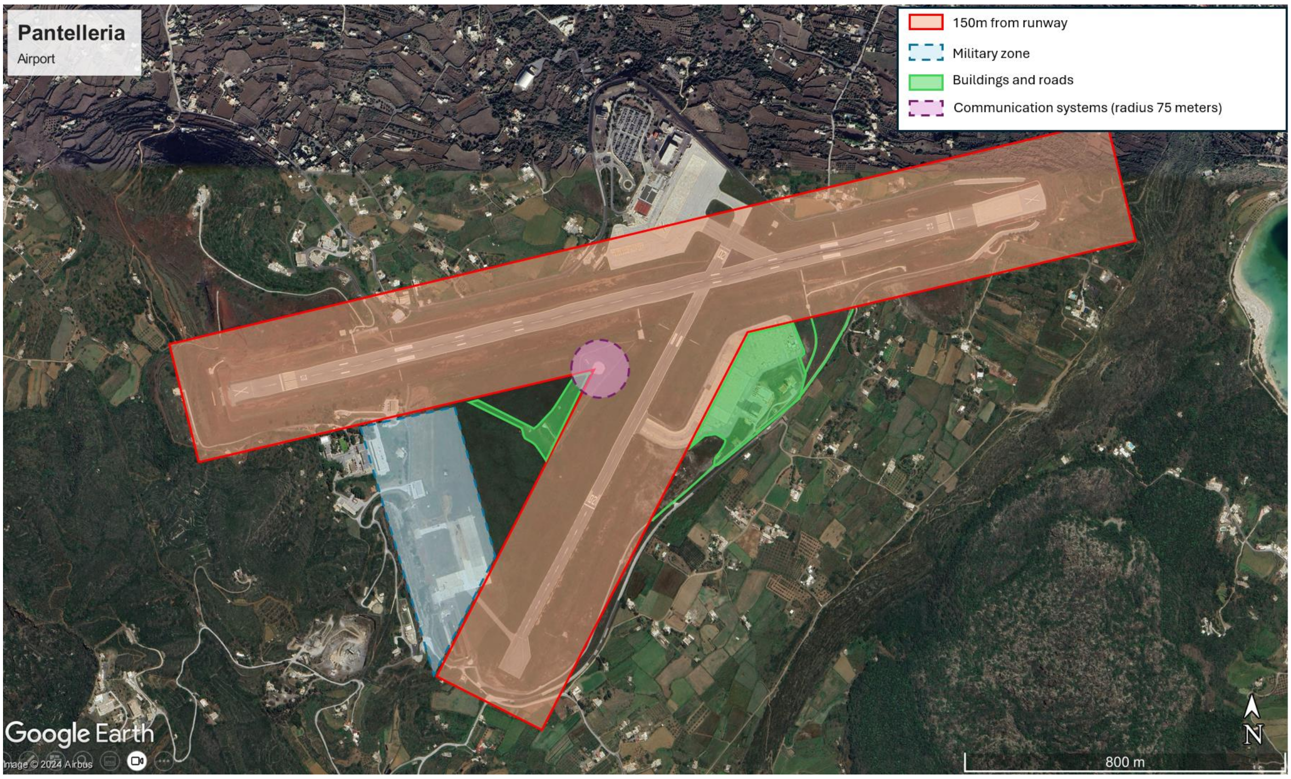

Figure 7: Constraints PV plant

2.4. Glare

Glare is a significant concern at airports due to its potential to distract or temporarily blind pilots, which could compromise both the safety and efficiency of flight operations. At airports, glare typically results from reflective surfaces, including solar panels, that can direct intense sunlight into a pilot's line of sight, especially during take-off and landing. This can hinder the pilot's ability to see important visual cues, such as runway markings, other aircraft, or obstacles in the vicinity of the airport.

Solar panels installed at or near airports can reflect sunlight in various directions. Depending on the placement, tilt, and azimuth of the panels, the reflected light can cause glare. To mitigate this risk, the installation of solar panels needs to be carefully planned, ensuring that the angles of reflection do not interfere with the flight path or the visibility required by the pilots for safe navigation.

To address glare risks, design tools such as SGHAT (Solar Glare Hazard Analysis Tool) are used [14]. SGHAT simulates potential glare hazards from solar energy systems and helps determine the optimal placement and orientation of the panels. By using these tools, it is possible to ensure that solar installations do not create dangerous glare effects for aviation operations. The approach is informed by international experiences, particularly from the Federal Aviation Administration (FAA), and advised by ENAC (Italian Civil Aviation Authority) [12].

2.5. Additional risk of bird strikes

An additional concern associated with the installation of solar PV arrays is the potential increase in the risk of bird strikes. A bird strike refers to a collision between a bird and an aircraft, typically occurring during take-off, landing, or low-altitude flight, posing risks to both aviation safety and wildlife. This concern arises from the possibility that birds may be attracted to areas beneath the solar PV arrays due to the shade they offer and the availability of food resources, such as insects.

However, this attraction is generally limited because airfield grasslands are actively managed to minimise wildlife presence. The shaded spaces under the panels can provide a resting area. However, while birds may perch under the solar panels, the risk of bird strikes is considered minimal. Research indicates that although small birds may use the PV arrays for shade, they are unlikely to fly in these areas, reducing the likelihood of collisions with aircraft [13] [16]. As a result, there will likely be fewer or an equal number of birds compared to PV plants in other environments.

It is important to monitor bird activity. If needed, extra preventive measures are possible, such as installing bird deterrents like metal spikes, can further mitigate any potential issues. While the presence of birds is a consideration, the overall risk to aircraft operations remains low based on current data and industry reports.

Figure 8: Metal spikes on PV modules to deter birds [17]

3. Design of the PV Plant

This section outlines the key considerations for the design of the PV plant. Key elements of the design include the choice of inverters, transformers, and the arrangement of PV panels to ensure optimal performance.

3.1. Tilt and azimuth

The tilt and azimuth angles are critical factors in determining the energy yield of a PV plant. However, these parameters also significantly influence the potential for glare, which is a key consideration in the proximity of airports. Managing glare is essential to prevent visual impairment for pilots during critical flight phases, such as take-off and landing.

The SGHAT (Solar Glare Hazard Analysis Tool) software, as described in Section 2.4, was used to conduct various simulations [18]. These simulations identified an optimal orientation of 180° (south-facing) for the azimuth and a tilt angle of 20°. The results indicated no glare risk for incoming flights.

It is important to note that the greatest risk of glare typically occurs when aircraft land in the direction toward which the solar panels are oriented. However, since no aircraft landed from the south on runway 03/21, this risk is minimal for this configuration. Given these preliminary simulations, the results should be interpreted with caution. Further verification of these findings with the national aviation authority is recommended in subsequent project stages.

3.2. Modules

The Vertex TSM-DEG21C.20 panels from Trina Solar were used for the design and simulation. This decision was based on several key factors:

- Anti-reflective coating: This is necessary to minimise the potential for reflection.
- Bloomberg Tier 1 Rating: Trina Solar is categorised as Bloomberg Tier 1, indicating their proven reliability, consistent performance, and adherence to high manufacturing standards. This classification also offers confidence in product warranties and support from a reputable supplier.
- Power Output of 655 Wp: The selected panels have a standard power output of 655 watts peak (Wp). This rating aligns with our system design objectives and ensures efficient land and structure use without compromising the energy yield.

3.3. Inverter

The Huawei SUN2000-330KTL and SUN2000-200KTL string inverters were used for the design and simulation. This decision was based on several key factors:

- The inverter offers up to 99% efficiency, minimising energy losses and maximising energy yield from the PV system.
- Designed to operate in a range of environmental conditions, with an IP66 protection rating against dust and water, ensuring long-term reliability in outdoor installations.
- At 330 kW and 200 kW, it is compact and lightweight compared to its capacity, making it efficient for large-scale installations requiring fewer units per site.
- It is widely used for ground-mounted PV installations due to its proven reliability, efficiency, and advanced features.

3.4. Grid connection

The figure below illustrates the grid connection points where the hybrid PV and BESS can be connected to the medium-voltage (MV) grid. These points are located in close proximity, which is advantageous as it minimises the need for extensive cable trenching, reducing installation costs and complexity. The grid nodes are connection points at 10.5 kV, which is an important factor to consider when sizing and selecting transformers. The suitability of a specific grid node should be further evaluated with the local DSO.

Figure 9: Grid nodes Pantelleria Airport

3.5. Design

Based on the sections 2.3 and 3.1 - 3.4, two available zones have been identified for PV installation (see Figure 10):

- One zone utilises the maximum area in the triangle between the two runways.
- The other two zones are on two additional areas on the eastern side of the airport.

Design parameters	
Inverters	Huawei SUN2000-330KTL 300 kVA Huawei SUN2000-200KTL 200 kVA
Module	Trinasolar Vertex TSM-DEG21C.20 655 Wp
Tilt	20°
Azimuth	180° South
Pitch	9 m
Distance from ground	1 m
Table size	2x8, 2x16, 2x24

Table 1: Design parameters PV installation

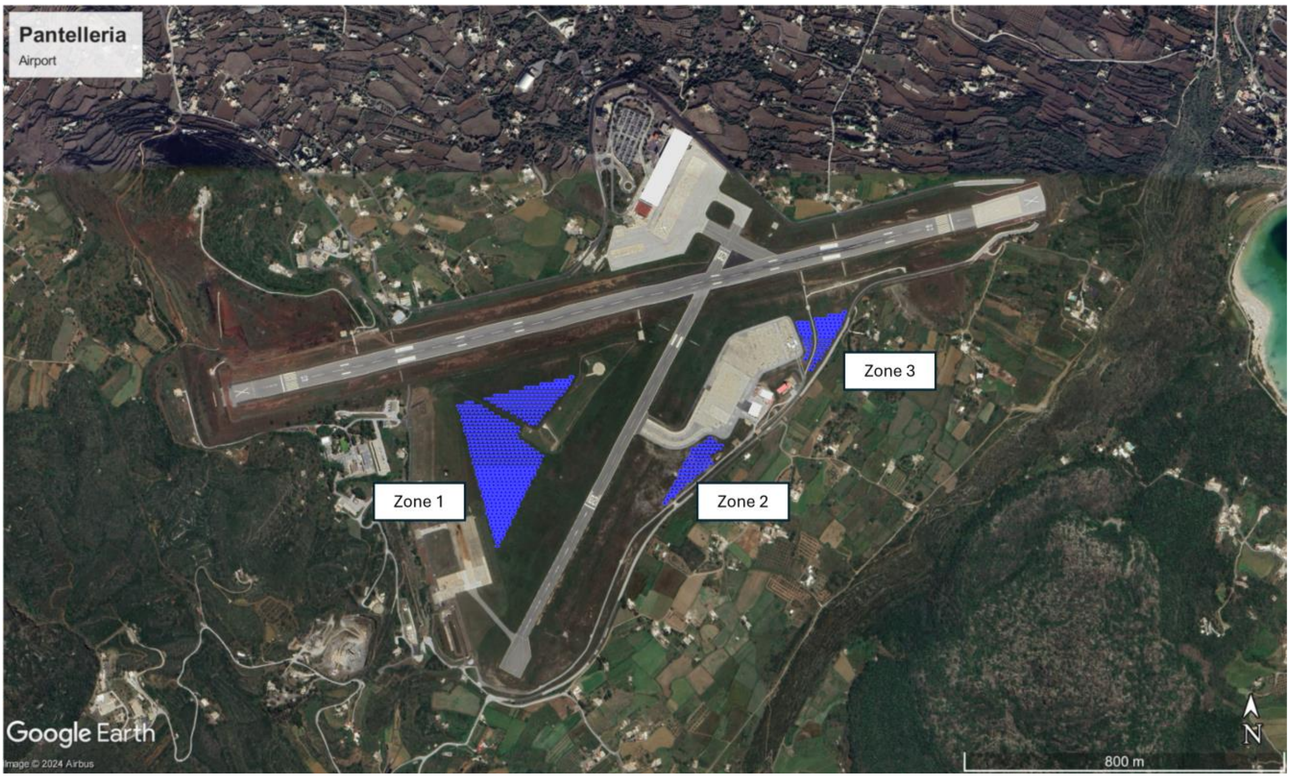

Figure 10: PV zones

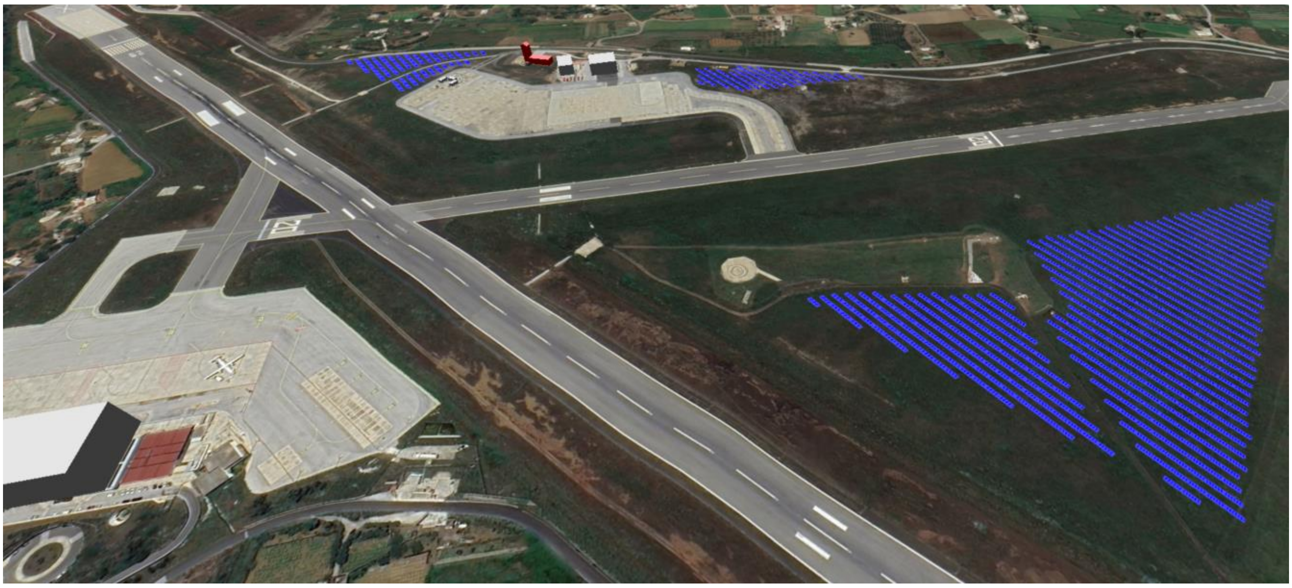

Figure 11: PV zones, view in perspective

Zone 1	
Available area	25795 m^2
Number of inverters	15 (300 kVA)
Number of modules	8’288
PV capacity	5429 kWp
AC power	4500 kVA

Table 2: PV installation zone 1

Zone 2	
Available area	3877 m²
Number of inverters	1 (300 kVA) and 2 (200 kVA)
Number of modules	1248
PV capacity	817 kWp
AC power	700 kVA

Table 3: PV installation zone 2

Zone 3	
Available area	3827 m²
Number of inverters	1 (300 kVA) and 2 (200 kVA)
Number of modules	1216
PV capacity	796 kWp
AC power	700 kVA

Table 4: PV installation zone 3

Figure 12: Zone 1

Figure 13: Zone 2 and 3

The transformers selected for this system are chosen to ensure optimal performance for each zone. Three transformers will be used for Zone 1, while a single transformer will be dedicated to Zones 2 and 3. This approach limits the number of medium voltage (MV) lines that need to be installed to connect to the grid connection points, and the same size of the transformer will be used, reducing the complexity and cost associated with the construction of the transformers and the MV lines.

Transformers Zone 1	
Total kWp power	5429 kWp
Total AC power inverters	4500 kVA
Voltage	10/0.8 kV
Amount of transformer	3
Capacity transformer	1500 kVa

Table 5: Transformers zone 1

Transformer Zones 2 and 3	
Total kWp power	1614 kWp
Total AC power inverters	1400 kVA
Voltage	10/0.8 kV
Amount of transformer	1
Capacity transformer	1500 kVa

Table 6: Transformer zones 2 and 3

3.6. Yield

The system performance was calculated by using dynamic models (PVSyst v7.2.14) as well as 3E's own assessment tool. These simulations were performed using the meteorological data from 2021, as the simulations for sizing the BESS will also rely on the island's 2021 load data. This is discussed further in the section about storage.

The meteorological data used in the simulation is from 3E Solar Data. 3E Solar Data makes use of the most advanced cloud physical properties (CPP) models to quantify the solar resource. The CPP algorithms derive cloud, precipitation, and radiation information from satellite instruments on board the Meteosat Second Generation (MSG) satellites from 2004 onwards. These physics-based, empirically adjusted algorithms enable the continuous monitoring of cloud physical properties and the quantification of their impact on surface solar irradiance.

The following parameters and assumptions were used in the simulations:

Parameter	**Assumption**
Horizon shading	The horizon line was considered. It was extracted from SolarGIS Prospect.
Dirt and soiling	Soiling losses were estimated at 2.5%, taking into account the high salinity of the air and the frequent Sahara sand deposits on the island, leading to the selection of a conservative value.
Near shading: irradiance loss	3E considered mutual shading losses based on objects close by.
Near shading: electrical loss according to strings	Simulations consider the PV modules are connected vertically with respect to the support structures. Tables with configuration of 2x8, 2x16, 2x24 have been considered for the project.

Reflection (IAM)	Standard glass parametrisation with an anti-reflective coating was considered (ASHRAE b0 = 0.04).
Irradiance dependencies	3E used the PV module file from the PVSyst database. It was verified according to the product datasheet.
Power tolerance of modules	3E assumed a quality gain of 0.2% based on the power tolerance stated in the product datasheet.
Temperature dependencies	Simulations consider the rear surface of the PV modules to be open (Uc=29 W/m^2.K).
Light induced degradation (initial)	LID is estimated at 1.3% for the selected modules.
Mismatching	Module mismatch losses were estimated at 0.4% for unsorted PV modules. String mismatch is assumed to be 0.1%.
DC cabling	DC cable loss is estimated at 1.5% at STC conditions.
Inverter	3E used the inverter file (OND file) from the PVSyst database. It was verified according to the product datasheet.
AC cabling	AC cable loss is estimated at 1% at STC conditions.
Transformer	3E considered iron loss to be 0.06% and copper 0.70% for 1500kVA oil-type transformers, which correspond to A0Ak according to the EU new norm (07/21).
Auxiliaries	Loss for auxiliaries was estimated at 0.3%.
Additional (e.g. line loss)	3E considered a cos(phi) equal to 98%.

Table 7: Paramaters simulations PVSyst

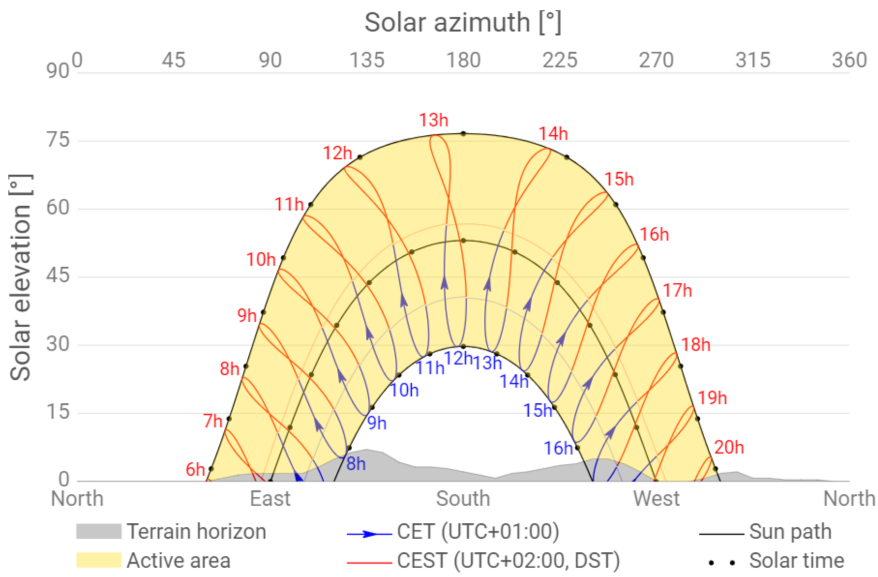

Figure 14: Iso-shading diagram

The results of the yield assessment are shown in the tables below. Since zones 1 and 2 are connected to the same transformer, their combined yield is calculated as a single value. This approach accounts for transformer losses, ensuring a more accurate assessment of the system's overall efficiency.

Results zone 1	
System production	9335.7 MWh/year
Specific production	1719.6 kWh/kWp/yr
Performance ratio at start-up	86.4%

Table 8: Results zone 1

Results zones 2 and 3	
System production	2877.1 MWh/year
Specific production	1781.5 kWh/kWp/yr
Performance ratio at start-up	86.6%

Table 9: Results zones 2 and 3

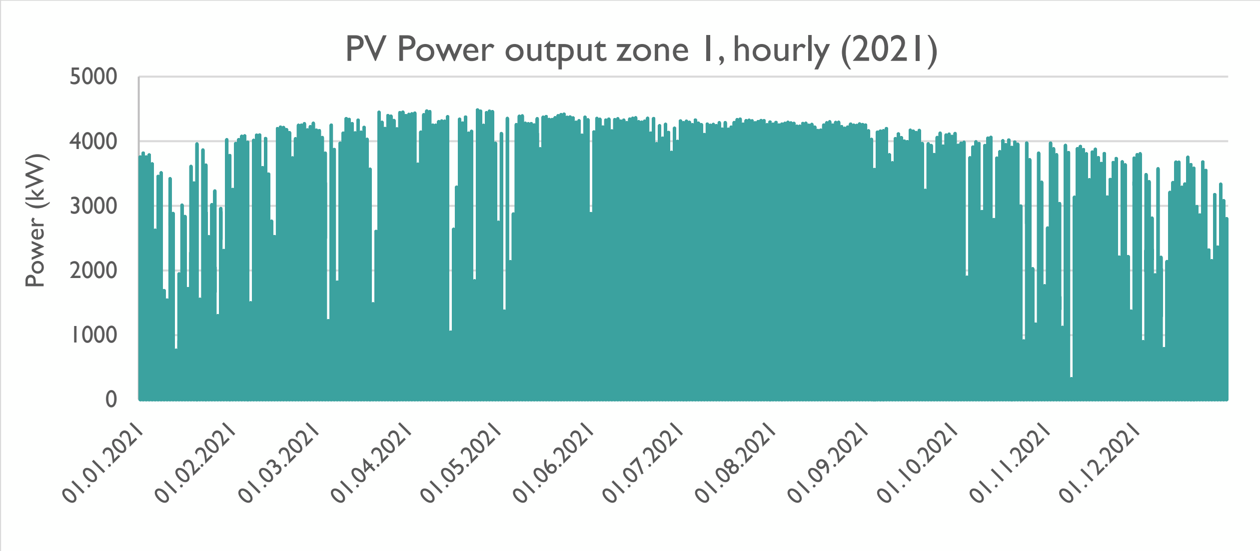

Figure 15: PV Power output zone 1, hourly (2021)

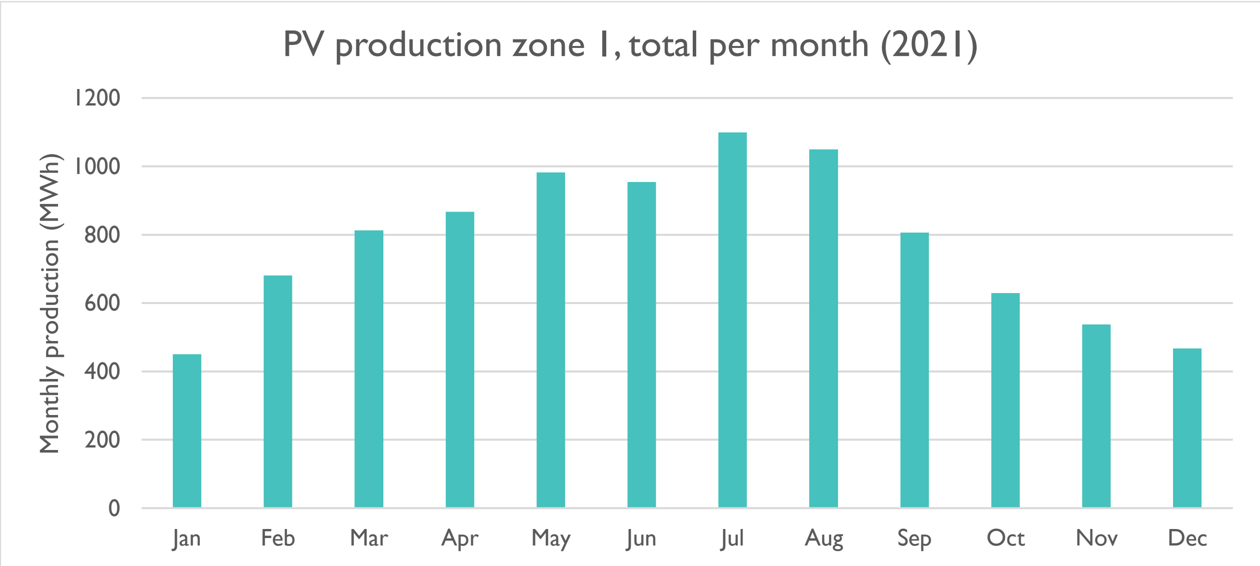

Figure 16: PV production zone 1, total per month (2021)

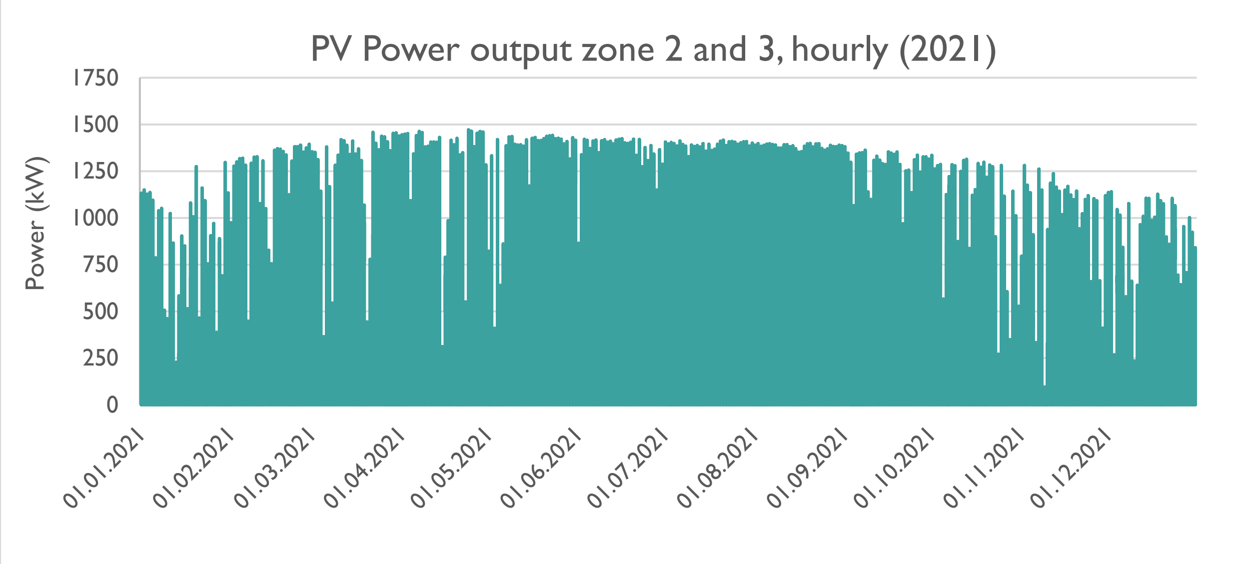

Figure 17: PV Power output zones 2 and 3, hourly (2021)

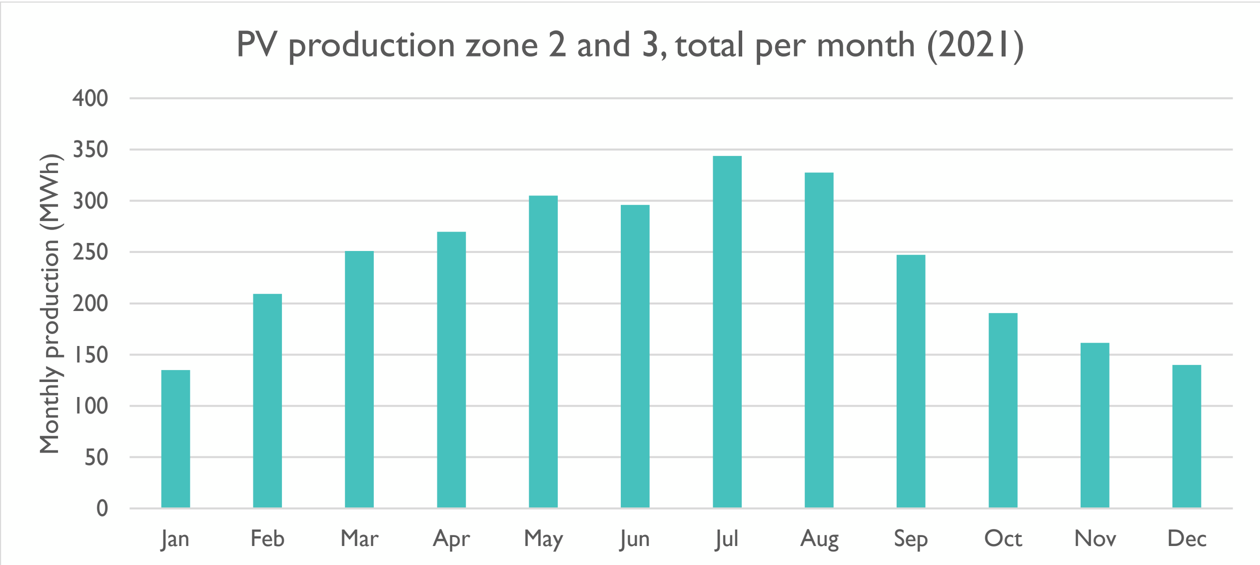

Figure 18: PV production zones 2 and 3, total per month (2021)

4. Battery Sizing for Technical and Economic Feasibility Assessment

Determining the optimal size of the storage system is a critical step in ensuring the effective integration of renewable energy production and the stability of the energy grid of Pantelleria. In this section, the methodology and the results to arrive at a feasible storage solution are discussed.

4.1. Methodology

4.1.1. Assumptions costs PV

The cost estimation for the PV installations for the zones is calculated by considering key components and services essential for setting up a ground-mounted solar system. The following cost elements are included in the Capital Expenditure (CAPEX) estimation:

- Procurement and Installation of PV Modules: The cost of acquiring and installing the Trinasolar Vertex TSM-DEG21C.20 655 Wp panels.
- Inverter Procurement and installation.
- Ground-Mounted Structure Procurement and Installation: Costs were allocated for the procurement of robust structures to support the PV modules. This includes installation expenses for anchoring these structures securely at the site.
- DC Cabling Procurement and Trenches: The necessary DC cabling and the trenching work.
- AC Cabling Procurement, LV Electrical Boards, and Trenching: The procurement and installation of AC cabling, low-voltage (LV) electrical boards, and trenching work for routing cables to the transformer station.
- Transformer Station: The cost of procuring and installing the transformer stations.
- Engineering, Procurement, and Construction (EPC) Costs:

For the estimated OPEX costs, regular maintenance, monitoring, and minor repairs are included. It is assumed that inverters will be replaced every 10 years at 50% of the original cost to account for their limited lifespan.

Based on previous experience with small islands in Sicily, the overall plant cost is estimated to be around 1,000 EUR/kW for the characteristics of this project. The resulting total CAPEX and OPEX for the PV installations in the different zones are shown below:

Costs	Zone 1	Zone 2 and 3
CAPEX (VAT excl.)	5400 k€	1600 k€
OPEX (O&M per year, VAT excl.)	23 k€	7 k€

Table 10: CAPEX and OPEX costs of PV installations

4.1.2. Assumptions costs BESS

The cost estimation for the BESS includes critical components and services necessary for its integration into Pantelleria's renewable energy system. The following cost elements were included in the Capital Expenditure (CAPEX) estimation:

- Storage Block Procurement and Installation: This includes the costs associated with acquiring the battery storage units and their installation on-site.
- Inverter Procurement and Installation: Inverters are crucial for converting the stored DC energy from the batteries into AC for grid usage. The budget covers the procurement and

installation of these inverters to ensure seamless integration with the existing energy infrastructure.

- Transformer Station: The cost of procurement and installation of one transformer station.
- Construction Management and Engineering: This includes the costs for on-site construction management and engineering services, such as site preparation, project supervision, and quality control during the installation phase.

The cost of the BESS is influenced by its storage capacity (kWh) and power rating (kWp). The estimated cost for storage capacity is approximately 280 EUR/kWh, while the power cost is estimated at 180 EUR/kW. These assumptions are valid for Li-ion storage with an energy-to-power ratio ranging from 0.5 to 4.

The yearly OPEX has been modelled as 2% of the CAPEX.

4.1.3. Scenarios and optimisations

The optimisations carried out in this report integrate the various techno-economic parameters discussed in previous sections, focusing on determining the size of the BESS required for the grid to accommodate the new PV plant. These optimisations are performed using the PyPSA framework (Python Power System Analysis) [19] [20], which defines the configuration and operation of energy systems to achieve the lowest annualised system cost, under a set of constraints developed for the specific case study.

In this specific case, PyPSA has been used to size the BESS associated with the new PV plant under a set of requirements to ensure grid stability and smooth integration of the PV plant in the island grid. The key settings and assumptions for the optimisations are as follows:

- Electric load: The electric load shared by the local DSO for the year 2021 has been used for the calculations. The overall power generation for that year amounted to 36.7 GWh/year.
- Generation load: The generation load was retrieved from historical meteorological data referred to the year 2021, based on the technical characteristics presented in Section 3.
- A time-step of 60 minutes has been used in the optimisations.
- Diesel plant: The power size of the diesel generation plant amounts to an overall 24.5 MW. The generation cost amounts to 426 EUR/MWh, plus 69 EUR/MW/h for the runtime.
- Grid stability:
  - Only the diesel generators have been considered to provide the reserve service.
  - The reserve request has been assumed to be equal to 10% of the total instantaneous load plus 10% of the total instantaneous available renewable power plus the size of the smallest diesel generator (1.3 MW).
- BESS: An energy-to-power ratio between 0.5 and 4 has been considered. This is a typical range for Li-ion batteries, to which the cost assumptions of Section 4.1.1 are referred.

Three different scenarios have been analysed:

- Base scenario: The base case assumes no new PV plant is added, with the existing 4 MW of distributed PV installations on Pantelleria and the existing BESS of 4 MW/4 MWh (the only variable used in the analysis is the BESS size).
- Base scenario with the new PV plant of zone 1 (in total 9.4 MW).
- Base scenario with the new PV plant of zones 1, 2 and 3 (in total, 11 MW).

Scenario	Existing PV	New PV	Total
Base scenario: 4 MW PV	4.0 MW	0 MW	4.0 MW
PV: 9.4 MW	4.0 MW	5.4 MW (Zone 1)	9.4 MW
PV: 11 MW	4.0 MW	7.0 MW (Zone 1, 2 and 3)	11.0 MW

Table 11: Scenarios

4.2. Results

This section presents the results of the optimisation performed in the various scenarios, illustrating the optimal BESS size for each case. The simulation results highlight the impact of adding new PV installations on Pantelleria and the corresponding adjustments to the BESS requirements for ensuring optimal energy system performance.

To maintain grid stability and lower operational costs, the current system requires an additional 1.2 MW power capacity and 4.7 MWh of storage. The share of Variable Renewable Energy Sources (VRES) in this scenario is limited to 23%, with almost no curtailment (<0.2%). This reflects the relatively small scale of renewable penetration compared to the island's energy needs.

Adding the 5.4 MW PV plant in Zone 1 necessitates increasing the total BESS capacity to 9.8 MW (power) and 27.3 MWh (energy), with 5.8 MW and 23.3 MWh being newly added. The share of VRES rises significantly to 44%, showing the growing reliance on renewable energy. However, 7.48% of PV electricity is curtailed.

The more extensive 11 MW PV system requires an even greater BESS capacity, totalling 11.4 MW (power) and 33.6 MWh (energy). Of this, 7.4 MW and 29.6 MWh are newly added. The share of VRES increases to 50%, approaching a majority share of the island’s energy production. Curtailment rises to 10.29%, highlighting the challenges of integrating additional renewable capacity without corresponding grid upgrades or demand-side solutions.

Scenario	Total Pow. Conv. BESS (MW)	Total BESS (MWh)	New Pow. Conv. BESS (MW)	New BESS (MWh)
Base scenario: 4 MW PV	5.2	8.7	1.20	4.70
PV: 9.4 MW	9.8	27.3	5.80	23.30
PV: 11 MW	11.4	33.6	7.40	29.60

Table 12: Results optimised size BESS

Scenario	Overall share VRES (%)	Generated electricity from PV (MWh)	Curtailed electricity from PV (MWh)	Curtailed electricity from PV (%)	Energy discharged from BESS (MWh)
Base scenario: 4 MW PV	23%	8284	16	0.19%	2390
PV: 9.4 MW	44%	16317	1320	7.48%	6878
PV: 11 MW	50%	18387	2108	10.29%	9’306

Table 13: Results Energy production and curtailment

The total costs for both the PV system and the BESS are presented in the overview below.

Costs	Base scenario	PV: 9.4 MW	PV: 11 MW
PV			
CAPEX (VAT excl.)	0 k€	5400 k€	7000 k€
OPEX (O&M per year, VAT excl.)	0 k€	23 k€	30 k€
BESS			
CAPEX (VAT excl.)	1500 k€	7600 k€	9600 k€
OPEX (O&M per year, VAT excl.)	30 k€	150 k€	190 k€
TOTAL			
CAPEX (VAT excl.)	1500 k€	13000 k€	16600 k€
OPEX (O&M per year, VAT excl.)	30 k€	173 k€	220 k€

Table 14: Total costs of PV system and BESS

5. Conclusions and Recommendations

5.1. Conclusion

This report examined the potential for integrating photovoltaic (PV) systems and battery energy storage systems (BESS) at Pantelleria Airport. The development of a hybrid PV-BESS plant at Pantelleria Airport represents a pivotal step toward achieving energy independence and sustainability on the island. Pantelleria can significantly reduce its reliance on imported fuels, lower greenhouse gas emissions, and stabilise energy costs.

The airport presents a strategic opportunity for a PV plant, given its large, underutilised surfaces. Regulatory and technical constraints, such as the 150-meter obstacle-free zone near the runway, potential interference with communication systems, glare risks, and bird strike considerations, were analysed. These constraints delineated the zones suitable for PV installation, enabling a detailed assessment of the feasible surface area for solar deployment. The analysis concluded that zones 1, 2, and 3 on the airport property could accommodate up to 11 MW of PV capacity, representing a significant increase over the existing installations.

The design of the proposed PV system incorporated optimal tilt and azimuth angles (20° tilt and 180° azimuth) to maximise energy yield while minimising glare risks. The yield assessment, based on historical meteorological data from 2021, demonstrated a substantial increase in annual energy production, especially with the inclusion of all three zones. However, as PV capacity increases, the risk of energy curtailment also rises, underscoring the importance of integrating an appropriately sized BESS.

Battery sizing was performed using the PyPSA framework, optimising storage power and energy capacity based on economic and technical constraints. The analysis revealed that larger PV systems require correspondingly larger BESS capacities, reducing curtailment and maximising energy utilisation. For the base scenario (4 MW of PV), the optimal BESS size was 5.2 MW/8.7 MWh. For the expanded scenarios (9.4 MW and 11 MW of PV), the optimal storage sizes increased to 9.8 MW/27.3 MWh and 11.4 MW/33.6 MWh, respectively. Increasing PV capacity substantially boosts the share of VRES, from 23% in the base scenario to 50% with 11 MW PV. Adding storage significantly reduces curtailment; however, even with larger BESS, some curtailment persists in high-PV scenarios, such as in the 11 MW scenario, where 10.29% of PV generation is curtailed. This is normal behaviour in non-interconnected power grids.

The outcomes were presented in a table, with the optimal configurations listed by the combination of storage power, storage capacity, and PV capacity. CAPEX and OPEX estimations were given, derived from previous experiences with similar projects.

5.2. Recommendations

The following key recommendations and suggestions for the hybrid PV and storage plant in Pantelleria Airport project continuation and implementation are given based on the outcomes achieved in this report:

- **Maximise Solar PV installation**: Expanding PV capacity is vital for Pantelleria to achieve energy independence and reduce dependence on fossil fuels. Utilising the airport area for solar PV installations ensures efficient use of the island's limited land, aligning with sustainability goals and energy demand requirements.

- **Interactions with the DSO**: Collaborate with the Distribution System Operator (DSO) to determine the optimal size and integration of both the PV plant and the BESS. Active communication to align with the connection capacities at the airport and integration with Pantelleria's distribution network.
- **Interactions with ENAC**: Engage with ENAC, the national aviation authority, to:
    - Agree on the availability of the area and identify the procurement options, also in view of Public-Private Partnerships.
    - Ensure an early communication of the requirements for compliance with aviation safety and operational regulations. This collaboration will streamline approvals and address any potential concerns regarding glare, communication interference, and bird strikes.
- **Kick-off discussions on financing the hybrid plant:** Collaborate with local and national stakeholders to identify and secure suitable financing mechanisms for the BESS. Indeed, whereas the PV plant is expected to be economically sustainable, the BESS system will most likely require funding from the national government or other available sources.

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