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Improving the Power Distribution Grid Resilience through the Integration of Distributed Energy Resources: Case Studies in Greece

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ABSTRACT

With the energy transition well underway, grid operators are increasingly facing the challenges of maintaining reliability but also ensuring the resilience of the energy system, i.e., its ability to adapt to changing conditions, as well as withstand and recover from disruptive events. Resilience becomes, hence, an emerging concept of top priority for power distribution utilities, encompassing the components of robustness, redundancy, resourcefulness, response, and recovery. In this context, the contribution of distributed energy resources to the power system resilience is crucial to be examined, since such resources can add flexibility capacity already from the planning stage. This paper aims to highlight the relation of grid resilience with renewable-integrated power grids and storage schemes by capturing lessons learned from case studies in Greece, such as residential (rooftop) applications and large-scale pilot projects. A holistic climate change adaptation approach aimed at grids to be resilient by design can mitigate climate-related disruptions, especially in highly vulnerable countries like Greece.

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Introduction

The energy transition represents a real change of paradigm at the distribution level, and Distribution System Operators (DSOs) are expected to become the backbone of the electricity system that will become the dominant energy carrier over the coming decades. In parallel, it is clear that the threat landscape at the global level is currently very complicated and DSOs are faced with concurrent challenges, such as:

- The need for transformation and fundamental changes both in assets and system operation towards the net zero emissions commitment (more grid investments, network reinforcement stemming from rapidly expanding distributed generation, increased network planning and forecasting of innovative technologies, flexibility management, etc.);
- The expansion of the scope of their responsibilities and the increasing expectation to take on a broader leadership role in the resilience of the communities they serve, including critical facilities, cyber-attacks, and societal outcomes;
- The impacts of climate change (i.e., changing trends, increasing variability, greater extremes, and large inter-annual variations in climate parameters in some regions) across the entire energy supply chain;
- The requirement to maintain at steep costs the aging network assets or proceed with essential renovations;
- The operational and regulatory implications of the above challenges, as well as the increased liability losses to third parties which in some cases come at a cost that utilities are unable to bear.

Nonetheless, climate change is considered one of the highest risks in severity that DSOs will face in the upcoming years. According to the Global Risks Report 2023 of the World Economic Forum, climate mitigation and adaptation efforts are set up for a risky trade-off [1]. Climate risks are the core focus of global risk perceptions over the next decade – and are the risks for which we are seen to be the least prepared. The discrepancy between what is politically practicable and what is scientifically required to reach the net zero target has been made clear by the lack of significant, coordinated progress on climate action targets.

The acceleration of the frequency and intensity of extreme climate incidents represents a multitude of risks for energy systems. Extreme temperatures, precipitation, and winds cause numerous breakdowns of the electricity networks. Indeed, in the EU, according to the monthly statistics of ENTSO-E, around 33% of the power interruptions between 2016 and 2020 were caused due to extreme weather [2]. In consequence, DSOs face large amounts of deterioration or even destruction of their infrastructure. They also need to mobilize emergency teams to fix the electricity grid and keep the lights on.

In this context, the concept of power system resilience emerges as an imperative need and is increasingly established as a policy priority, especially for critical entities. However, resilience is not a very new concern in Europe and it has been included as a term in major regulations (i.e., Regulation (EC) No 714/2009 of the European Parliament and the Council, Regulation (EU) No 347/2013 of the European Parliament and of the Council). Resilience is even more important for today's power companies, though, due to the growing concern over the disastrous effects of climate change on grid infrastructure.

The definition of resilience has generated an intricate and continuous discussion due to its multifaceted nature, encompassing several aspects such as the correlation between resilience and reliability, event-specific vs agnostic, and qualitative versus quantitative indices [3,4]. According to the Intergovernmental Panel on Climate Change (IPCC), a system's resilience is defined as its ability to anticipate, absorb, and recover from the effects of harmful events efficiently and within a reasonable timeframe. The US Federal Energy Regulatory Commission defines grid resilience as the "ability to withstand and reduce the magnitude and/or duration of disruptive events, which includes the capability to anticipate, absorb, adapt to, and/or rapidly recover from such an event". While power distribution networks have traditionally been regarded as reliable (mainly concerning energy supply) against the most common threats, recent extreme weather events from around the world have highlighted the growing importance for distribution grids to achieve high levels of resilience as well, to mitigate the effects of low-probability, high-risk events and recover quickly. As shown in the graph below, resilience is divided into operational and infrastructure resilience. Following a system degradation, the key is to absorb the shock, bounce back to normal operation with minimal downtime or business disruptions, and adapt operation.

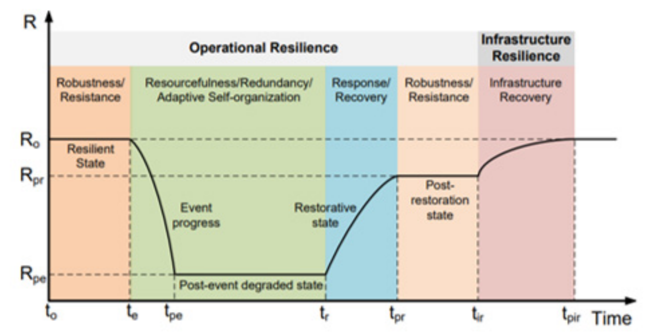

Figure 1: Operational vs Infrastructure Resilience [5].

The Roadmap towards Resilience

Initiatives for Building Power Grid Resilience

Extreme weather events present risks to grid integrity. For instance, flooding can inundate key infrastructure, such as substations or transformers, blacking out large areas; high winds can down overhead power lines; extreme heat can cause electricity demand to exceed system capacity, and also cause lines to sag into trees. Hence, withstanding and quickly recovering from such incidents must be a critical function of modern power distribution grids. An effective resilience enhancement strategy is based on the following pillars:

- **Hardening the Grid:** Hardening means strengthening the network by applying a variety of solutions such as raising seawalls around key assets, restoring natural coastal protections, undergrounding overhead power lines, relocating key assets, replacing wooden poles with concrete ones, improving line materials, such as high-temperature, low-sag conductors, and expanding tree-trimming programs. However, although these measures can be simple in concept, they must be resilient for the long term, considering future changes in sea level, temperatures, storm intensity, etc.

- **Smartening the Grid:** In recent years, utilities have begun to deploy smart grid technologies, from advanced metering at the customer level to enable automatic outage detection and service restoration, to sensors and controls to enable rapid detection, isolation, and restoration of service at the circuit and substation levels. After an event, the data collected through these technologies can be used to find opportunities for further resilience improvements.

- **Distributing Generation:** Extreme weather can force power outages by driving power demand past the limits of available generation resources. Damage to the distribution system also limits restoration efforts, even if generation capacity is available. One practice applied in other countries is to increase distributed generation (DG) resources; by increasing the number of generation sources, diversifying their fuel types, and locating them in a more distributed fashion around the service area, DG can both limit the risk of outages and allow faster restoration of service. Long-term access to reliable energy through distributed RES reduces vulnerability of local communities to climate change and increases their capacity for self-resilience and adaptation, without needing significant upfront infrastructure investment [6]. Nonetheless, DG poses challenges to utilities to fully integrate such resources into planning and operational practices.

- **Optimizing Business Operations:** Enhanced business operations support organizational resilience, which is the capacity of an organization to anticipate, prepare for, respond to, and learn from disruptions, crises, and opportunities. It is not just about surviving a shock or bouncing back, but also about evolving and growing stronger from the experience. Towards this direction, power utilities should establish robust business operations frameworks to guide the design, execution, and improvement of business processes, systems, and resources. These frameworks provide a clear and consistent way of defining roles, responsibilities, standards, and expectations to reduce ambiguity, confusion, and errors. They also enable organizations to adapt to uncertainty and changing conditions, by supporting them to anticipate risks, threats, and vulnerabilities. Indicative actions include emergency exercises, crisis management workshops, disaster and crisis management planning, etc.

The above actions should be supported by R&D initiatives and pilot projects.

The Integration of Distributed Generation Resources

As the frequency and magnitude of extreme weather incidents become more difficult to forecast because of climate change, large generators and power grids become easier to fail and harder to restore [7]. On the other hand, enabling a wide portfolio of DG such as solar plus batteries and microgrids can make the overall energy system more versatile and efficient and less prone to power outages or supply problems, thus demonstrating proven resilience benefits associated with the ongoing evolution of grid technologies [8-11]. When centralized systems are disabled by a disaster, DG can enable some parts of the grid to operate and serve critical loads. In this case, production loss can be only partial during long-duration outages on the broader electricity grid (thus leading to limited voltage disruptions at the local level in comparison with the disruption that would have been caused by the loss of a large production unit). Moreover, the shift to serving loads with decentralized and more DG has driven the need for network renovation and modernization using telemetering [12]. The traditional supervisory control and data acquisition (SCADA)-based control and monitoring of power systems is reliant on sensors, monitored by intelligent electronic devices (IEDs), which can facilitate restoration efforts.

Furthermore, storage technologies (i.e., batteries) coupled with renewable energy sources (RES) can provide power support to local autonomous grids or weak grids inside islanding areas during long-duration outages on the broader electricity grid, maximize the contribution of RES, whilst they can provide ancillary services for the DSOs, such as voltage and frequency regulation and reactive power support.

Microgrids (MGs) have also gained a lot of attention in the power system market while constituting a strategy to increase energy resilience and enhance the ability to serve an installation's electrical loads during a contingency situation. MGs are small-scale energy systems including DG located close to the local load demand, energy storage and control units which could work in a grid-connected or off-grid mode, ensuring the power supply for a defined region [13]. Hence, they tend to become both the source of energy generation and consumption simultaneously. Microgrid solutions can integrate with the grid to be part of its operational and resource mix, and can also "island" and operate autonomously, if needed, to keep running during grid outages, thus providing a reliable power source to critical infrastructure facilities, like hospitals, emergency centers, military installations, etc.

Due to their ability to operate in a controlled, coordinated way, when connected to the main power grid and in islanded mode during disturbances, resilience is enhanced as follows (see Figure below) [14]:

- **Resilience at the Distribution Level:** MGs connected to the distribution system (MG2-MG4) can function as power sources to supply the local demand of the distribution system if a failure isolates the distribution system. Furthermore, to reduce load shedding, the distribution system may be divided into self-sufficient MGs by leveraging the numerous connected DERs.

- **Resilience at the MG Level:** If an individual MG (MG4) is isolated due to a failure in the distribution system, it can effectively operate in islanded mode by appropriately allocating its resources to meet its minimum critical load.

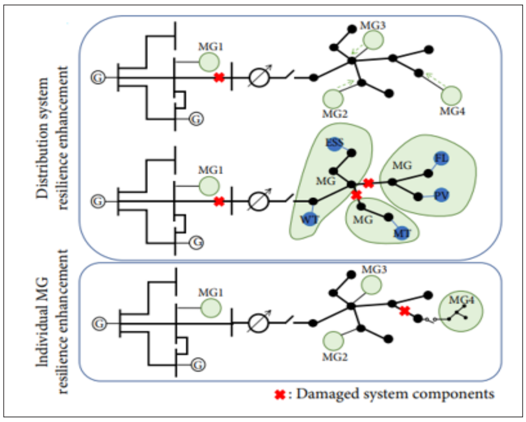

Figure 2: The Role of Microgrids for System Resilience [14].

In the future, an energy community could constitute a MG to ensure the power supply of the community's consumers.

Challenges for the Transition to Islanded Mode

The planning and operation of electricity distribution grids are undergoing significant changes due to RES integration. Uncertainty analysis should be considered for both generator scheduling and for evaluating physical vulnerabilities, i.e., natural disasters. Furthermore, the multiplication of smart electronic devices to enable DERs has contributed to the grid's increased digitalization, which raises cybersecurity concerns and necessitates monitoring [12].

Hence, although the MG concept and its benefits buck the trend of reliance on centralized systems, their operation management is essential to mitigate the unbalanced power supply and increase its quality in the case of disconnection from the grid [13]. To fully utilize dynamic entities such as MGs, more intelligent control and improved monitoring are needed. MGs need to be able to operate both autonomously and intelligently when connected to the grid. There are also many technical challenges for the effective transition into the islanded mode of operation [15]:

- **Earth Fault Protection Requirements:** The earthing requirements should be revised to ensure sufficient protection both in grid-connected and islanded modes of operation.

- **Quality of Supply to Customers:** The operation of portions of the network in islanded mode may create some difficulties in the operation of distribution network automation systems and affect the continuity of supply. Faults on networks cause interruptions, increasing the related indexes, i.e., System Average Interruption Duration Index (SAIDI) and System Average Interruption Frequency Index (SAIFI). During the operative cycles of the circuit breaker operating in automation and where the automation relies on voltage sensing, there could be a significant degradation of automation's effectiveness.

- **Synchronizing & Reclosing Issues:** Synchronization needs a way of comparing the voltages between the island and the system with the appropriate measuring and control equipment to ensure the voltage differences, in phase and magnitude, are within safe limits before reclosing the switch. Thus, switching points need to be appropriately equipped to perform synchronization. Almost none of this equipment currently exists in DSOs' substations because there has been no need.

- **Regulatory and Market Issues:** During normal operation, customers receive power at frequencies and voltages within precisely defined ranges. However, when an unintended island has formed, the supply-dispatch-frequency management responsibili-ty is currently not determined through regulations:
  - No single party is structurally in control of frequency or voltage.
  - DSOs do not have contracts to dispatch generation connected to their networks.
  - In many EU countries, there is no clear regulatory or legal framework for the liability of DSOs for islanded operation outside of normal voltage and frequency limits, nor for the risks posed by unearthed and/or unprotected operation.

Case Studies in Greece

Being highly vulnerable to the effects of climate change, and in alignment with the ambitious European goals for climate neutrality by 2050, the Hellenic Electricity Distribution Network Operator

(HEDNO S.A.) has taken several actions for the promotion of renewables in Greece. More specifically, HEDNO closed the year 2022 with a total power of 6.5 GW, i.e., an increase of 64% between the period 2019-2022. The total power is estimated to have exceeded 8.7GW at the end of 2023, while, according to HEDNO's planning, the total power is estimated to reach around 10GW in 2024. The interconnection of islands is also a point to consider since it can enhance the stability and resilience of systems that have been weak up to now.

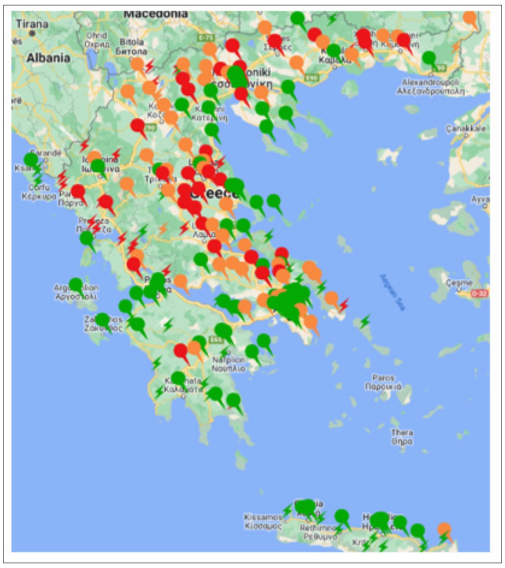

Figure 3: The Renewables Landscape in Greece – Power Absorption Capabilities. (Source: HEDNO S.A.)

The above Figure illustrates the renewables landscape in Greece, based on data provided by HEDNO at the end of 2023. The map shows the saturated regions (red), regions with limited capacity (orange), and regions with available hosting capacity (green). The red regions have reached high levels of RES penetration, meaning that RES could be utilized to improve resilience.

Residential (Rooftop) Applications

In Greece, a subsidy program is established for residential applications up to 10kW (PVs and batteries). According to the program, the excess energy from a PV plant installed at the premises of a consumer is injected into the grid and can be used at a later time to offset consumption during times when onsite generation is absent or not sufficient. The Battery Energy Storage System (BESS) is operated to increase the PV self-consumption so that the energy absorbed by the grid is reduced. As presented in Figure 4, the PV energy is stored at noon hours to be used at afternoon hours. Since regulated charges are mainly volumetric-based (i.e., imposed in the amount of energy absorbed), the prosumer can achieve an extra reduction to his/her bill.

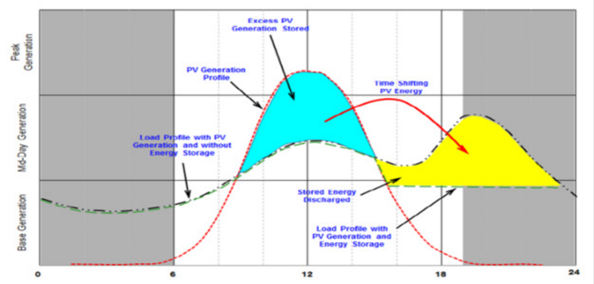

Figure 4: The Role of Microgrids for System Resilience.

The operating modes of a BESS are described in detail in the following Table. The safety control of the installation is required for both operating modes.

Table 1: Operation of a Battery Energy Storage System (BESS)

Mode of Operation	Description
Normal Operating Conditions	• If PV production is higher than the load, then the battery is charged AND when the battery is full, power is injected from the PV into the main grid • If PV production is lower than the Load, then the battery is discharged AND when the battery is empty, power is absorbed by the main grid
In case of emergency	• The battery undertakes the role of the main grid AND self-production must cover at least the critical loads • In this case, the following must be noted: o The inverters should be appropriately specified to be able to operate in islanded mode. o The DSO determines the requirements so that there is no power injection into the grid. o The switching device from the connected to islanded mode should have a "Loss of Mains" protection.

Indicative configurations of residential applications with PVs and storage are presented in the following Figures 5-7.

- **Configuration 1:** Power Supply from BESS: After grid failure, the PV inverter is disconnected from the grid due to its "Loss of Mains" protection. The BESS converter remains connected and supplies the loads inside the installation.
- **Configuration 2:** Power Supply from BESS & PV: The whole installation is disconnected from the grid and the hybrid converter remains connected to supply the loads.
- **Configuration 3:** Power Supply of Critical Loads from BESS & PV: The hybrid converter possesses one output for normal operation that is disconnected during grid failure and a second "emergency" output used to supply critical loads, which are separated from the installation in case of grid failure.

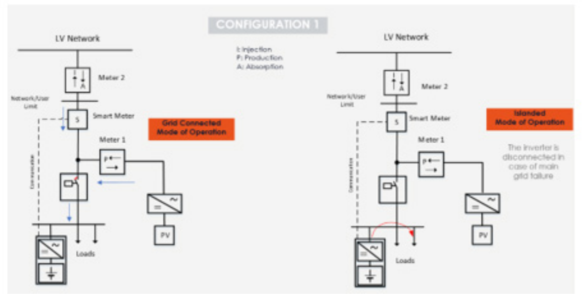

Figure 5: Configuration 1 of Residential Application – Power Supply from BESS.

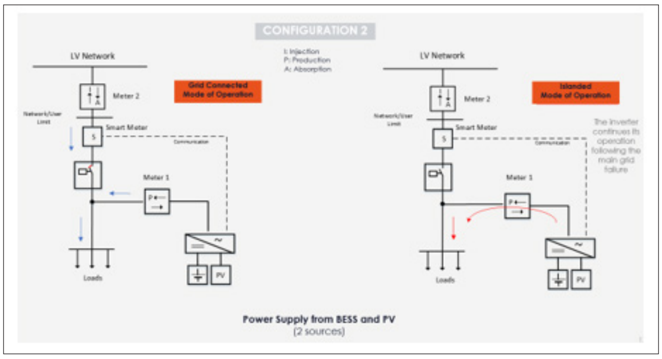

Figure 6: Configuration 2 of Residential Application – Power Supply from BESS and PV.

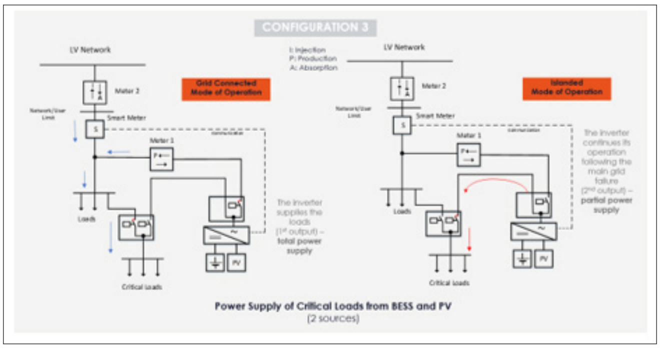

Figure 7: Configuration 3 of Residential Application – Power Supply of Critical Loads from BESS and PV.

Large-scale Pilot Projects

The Tilos Hybrid Microgrid

To ameliorate energy supply security and energy autonomy of the Aegean islands, an integrated solution was deployed in the Greek Tilos Island in the framework of the Tilos-Horizon 2020 program. Standing at a distance of 240 n. miles from the Greek mainland, Tilos belongs to a very special group of remote, small-scale European islands. The solution was based on the exploitation of the existing RES potential in conjunction with the application of an appropriate energy storage scheme, and complementary smart-grid elements [16].

Given the successful implementation of the Tilos project the first-ever batter-based, wind, and PV hybrid power station in Greece has been developed. At the same time, an integrated MG has also been developed on the island and several innovative elements have been introduced, altogether transforming Tilos into an exemplary island case in terms of local-scale clean energy production and management. This comprised a breakthrough, not only for Tilos but also for the Greek market as a whole, disrupting the norms of the past and presenting a new energy paradigm and solution for the electrification of island regions. The integrated Tilos energy solution suggests an energy MG that is normally found to interact with the host electricity system of Kos and Kalymnos, or, in rare cases, operated in isolation (such as in cases of emergency or MG testing).

Figure 8: Description of Tilos Island MG and Geographical Location of Main Assets [17].

Concerning the power generation sector, the main assets that are currently in operation on Tilos include [16]:

- Tilos hybrid power station, comprising an 800 kW medium-scale wind turbine, a 160 kWp PV station, and an 800 kW / 2.88 MWh integrated BESS.

- The backup diesel genset of 1.45 MW.

- Distributed, small-scale PV installations supporting early prosumer schemes including two monitored.

PV installations (capacity of 3.36 kWp at local residence and 4.93 kWp at the Tilos info-kiosk / EV charging station respectively) and four non-monitored PV installations (capacity of ~ 10kWp in total).

The Tilos island MG is a great success story introducing several important innovative characteristics in the European market, like the combined operation of a wind turbine and a PV installation, the application of new technology BESS, the installation of a DSM network/platform and the development of a large number of reliable forecasting algorithms.

The Lighthouse Project in Chania Airport

The Lighthouse Project in Chania Airport is particularly pioneering in a traditional source of pollutants to drastically reduce the plant's environmental footprint. It includes the conversion of Chania Military Airport (115 Combat Wing) into a "green" military unit, covering all needs for electricity, heating, and cooling of the facilities 100% from RES. As part of the project, the facility is equipped with state-of-the-art intelligent energy management systems, without reducing its operational capabilities in any way. The total Capital Expenditures for the entire system were equal to 3,5 M€, while the annual benefit of the Unit's complete exemption from the cost of supplying electricity and meeting heating needs will exceed 400,000 €.

It is worth mentioning that Chania Airport was one of the world's first facilities to receive Net Zero Energy Airport & Net Zero Carbon Emissions Airport Certifications. The Table below provides a short description of the project services and equipment, as well as the certifications gained.

Table 2: The Lighthouse Project in Chania Airport in a Nutshell

Category	Description
Services	• Interventions in the AC systems and lighting of buildings and facilities to save energy and create thermal comfort for Combat Wing staff • Training of the appropriate technical staff of the Air Force for the needs of business operation, monitoring, and maintenance of the entire system. • System design and annual production considered the future heavy use of electric vehicles and their charging inside the Combat Wing
Equipment	• PV installation of 1.7 MWp (net metering scheme), to completely exempt the Unit from the cost of supplying electricity which currently exceeds € 400,000 / year. The power of the PV was calculated based on the annual needs increased by 20% due to the addition of the electrification load and future needs. The power factor has been regulated to be equal to 1 – the compensation of reactive power has been accomplished through innovative equipment • An energy storage system with very large capacity Lithium-ion cells using liquid-cooled batteries - to ensure an uninterrupted power supply for the airport, even during grid outages, for days or even weeks based on weather conditions. A seamless connection/reconnection of the batteries has been achieved for an uninterruptible power supply of loads in case of a power outage (synchronization check for voltage, frequency, and phase). Tests have been completed and have confirmed the continuity of supply upon power disruptions or interruptions. • Smart energy management and control system of the energy produced and consumed at the plant's facilities, to enhance resiliency and substantially improve energy efficiency. • Electric car charging infrastructure to electrify transport with RES and exempt it from the use of fossil fuels • Supply of electric bicycles for professional use
Certifications (expected to be concluded in the upcoming period)	• Certification as a Net Zero Carbon Emissions facility based on the Carbon Accreditation program of the Airport Council International (ACI) • Certification as Net Zero Energy Airport according to the National Laboratory of the US Department of Energy for Military Installation specifications

The installation includes the following equipment:

- Trina Solar PV Panels
- Inverter PV and converter BESS: Power Electronics (central)
- BESS: Leclanche, CATL LFP cells, liquid-cooled, with a lifespan of 6,000 cycles for charge/discharge from 2,5% to 100% (2.6 MWh)
- Steel base structure with magnelis coating

The MG is connected to the MV grid through a circuit breaker with the appropriate protection schemes imposed by the DSO, and a synchronism check to ensure that when the MG is connected to the grid, the voltage vectors do not differ. During grid failure, this circuit breaker 'opens', while the rest three downstream circuit breakers, protecting the loads, the PV, and the BESS, remain 'closed' to permit the energy flow from BESS and/or PV to the loads. Only in case green energy is not sufficient, the backup generator starts to operate. Indicative photos of the project are presented in Figure 10.

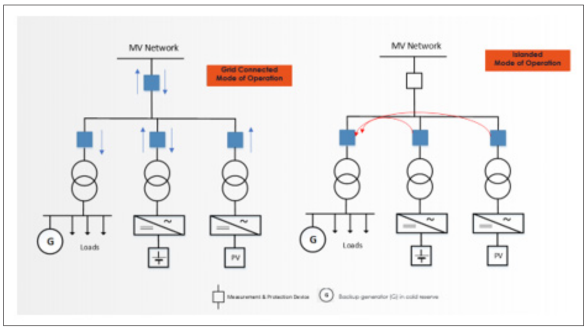

Figure 9: The Lighthouse Project in Chania Airport - Grid-connected and Islanded Modes of Operation

Figure 10: The Lighthouse Project in Chania Airport: PV panels and BESS (Source: HEDNO S.A.).

Conclusion

The energy transition poses new challenges for the DSOs. Significant grid development will be required in the longer term; it is estimated that annual investments in distribution grids should increase from 50% to 70% over the period 2020-2030. Moreover, to be able to connect RES and new loads, grids will need to be significantly expanded and reinforced. In addition, they will need to be modernized, since they are still relatively “blind”. To properly manage the future system, much more observability and controllability will be required. In this context, DSOs should also focus on enhancing system’s adaptive capacity to withstand potentially disruptive events through infrastructure hardening (hard resilience / focus on resistance) and on improving system’s coping capacity so that, if disrupted, it can rapidly recover operations, minimizing downtime and maintaining an adequate functionality (soft resilience / focus on absorption). Potential future research could integrate forecasting load demand and renewable generation models to remove the uncertainty of using historical data.

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