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RES curtailments in Cyprus: A review of technical constraints and solutions

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ABSTRACT

The increasing penetration of renewable energy sources (RES) in small, isolated power systems such as Cyprus has led to significant curtailments due to technical constraints, resulting in substantial energy losses and economic impacts. This study analyzes the drivers, trends, and mitigation strategies for RES curtailments in Cyprus, where annual curtailment rates surged from 2 % (2022) to 13 % (2024), with monthly photovoltaic (PV) curtailment exceeding 28 % during low-demand periods. System-wide constraints, particularly minimum inertia requirements and ramp rate limitations of conventional generators, dominate curtailment causes, exacerbated by Cyprus's seasonal demand variability and a 780 MW PV installed capacity. Historical data reveal a 500 % increase in high-curtailment days (≥200 MWh) from 2022 to 2024, with simulations forecasting further escalation as PV capacity approaches 1 GW by 2027. Operational procedures prioritize curtailing large-scale RES installations first, thus raising equity concerns for disproportionately affected stakeholders. Mitigation strategies evaluated include infrastructure enhancements like the 1 GW HVDC Great Sea Interconnector and retrofitting aging plants as synchronous condensers to bolster inertia, alongside operational measures such as energy storage systems (ESS)—deploying 80 MW/240 MWh batteries could reduce curtailments to 10 % by 2025. Demand-side flexibility, particularly elastic electric vehicle charging, and AI-enhanced forecasting are identified as cost-effective supplements. However, reducing the minimum stable generation level (MSGL) to accommodate higher RES penetration risks frequency instability, as demonstrated by transient simulations showing critical rate of change of frequency (RoCoF) thresholds exceeding 1 Hz/s during generator outages. The study concludes that a hybrid approach combining grid reinforcement, ESS deployment, and market-driven demand response is essential to align Cyprus's RES growth with EU decarbonization targets while ensuring grid reliability.

1. Introduction

Over the last decade, the penetration of Renewable Energy Sources (RES) has increased significantly due to environmental and economic concerns [1]. Compared to conventional, large, centralized generation units, RES technologies have some noticeable disadvantages that hinder the secure operation of power systems. These disadvantages are emerging mainly due to their stochastic nature leading to intermittent generation and the fact that they are mainly interfaced through power electronic devices [2].

The most common challenges facing electricity grids with high penetration of RES are network congestion, reduction in system strength, and reduction in voltage and frequency security [3]. There are several solutions proposed in the literature that can mitigate the impact of massive penetration of RES on electric power systems. These solutions are mainly split into two categories: solutions that target infrastructure enhancement (e.g., network reinforcement, interconnections with other power systems, etc.) and solutions that increase the grid flexibility (e.g., installation of energy storage systems, synchronous condensers, smart controllers, advanced monitoring, etc.) [4–6].

However, in many isolated power systems where these solutions have not been implemented yet, curtailment of RES generation is used to provide the necessary flexibility and resolve the technical constraints. RES energy curtailment refers to available RES energy that is dispatched

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down and is thus “lost” [7]. This curtailment can be imposed either by localized network issues (e.g., due to network congestion or voltage violations) or due to system-wide reasons (e.g., due to low inertia or system strength) [8,9].

Both the reasoning behind curtailments and their implication, as well as ways to decrease the levels of curtailment, have been the focus of various studies over the past few years. Bird et al. [8], presented a comprehensive review of the curtailment experience of wind and solar energy (levels of curtailment, the causes of curtailment, curtailment methods and use of market-based dispatch), with a focus on eleven countries in Europe, North America, and Asia. Furthermore, in O’Shaughnessy et al. [10] it was shown that in 2018, about 6.5 million MWh of PV output was curtailed in Chile, China, Germany, and the United States. They have found that some PV curtailment is attributable (a) to limited transmission capacity connecting remote solar resources to load centers and, (b) in spring and fall, when PV output is relatively high, but electricity demand is relatively low.

In line with Japan’s 2030 energy goals, RES penetration has been steadily increasing on the island of Kyushu, leading to the first-ever RES curtailment in Japan in October 2018, as reported by Bunodiere and Soo Lee [11]. RES curtailments are expected to worsen, and as reported by the authors, a 13.7 % curtailment level occured in April 2019, resulted in approximately ¥9.6 billion of wasted energy. Similarly, Jeju Island aims to replace conventional generators with distributed energy resources (DERs), and Lee et al. [12] estimated the annual RES curtailment for the stable operation of the islanded power system based on the hourly net load profile, showing that revised Time-of-Use (ToU) tariff rates are a reasonable and cost-effective scheme that can decrease RES curtailment levels.

Song et al. [13] have developed a new analysis method to investigate the optimal capacities of PV panels, wind turbines, and batteries for remote islands, to decrease total electricity curtailments. Cordova et al. [14], analyzed various scenarios to find a strategy to reduce energy curtailment in the power system of San Cristobal in Galapagos by evaluating multiple alternatives for energy storage. Moreover, Imanaka et al. [15] investigated the effect of Demand Response (DR) of heat pump water heaters and battery energy storage systems on reducing curtailment and constructed an optimization model of the isolated power system with several DR resources.

David [16] has demonstrated that increasing maximum nonsynchronous penetration (SNSP) from 75 % to 85 % reduces curtailment from 13.3 % to 8.0 %, saving 1338 GWh/yr of spilled wind. SNSP is the percentage ratio of the sum of the nonsynchronous generation plus net interconnector imports to the total demand including net interconnector exports [17]. Also, adding the Celtic Link of 700 MW at SNSP of 75 % reduces curtailment to 12.4 % and saves 235 GWh. Furthermore, it was estimated that the installation of 100 MW of batteries can save up to 19 GWh/yr.

In this paper, we focus mainly on curtailments due to system-wide reasons, which are the more dominant in islanded grids. Emphasis is given on curtailments due to the minimum inertia requirements which is the most common need for curtailment in Cyprus. The analysis is performed using the system of Cyprus, where a large amount of energy from RES has been curtailed in the last years to ensure the system security. A statistical analysis is performed and presented of the percentages of curtailments in Cyprus for the years 2022, 2023 and 2024. The data is provided by the Transmission System Operator - Cyprus (TSOC) and the Distribution System Operator of the Electricity Authority of Cyprus (DSO). To evaluate the reasons why RES curtailments must be performed, simulations are performed using the detailed dynamic model of the Cyprus Transmission System. The procedure utilized for curtailing RES by the Cypriot system operators are presented. Finally, recommendations are discussed to reduce the amount of RES curtailments based on established solutions that increase the system flexibility. While the Cyprus system is used as the basis for this analysis, the insights extracted are applicable to other small, isolated electricity grids.

The contributions of the manuscript are summarized as follow:

- Provides a thorough investigation of the requirements for curtailing renewable energy sources (RES) in low-inertia isolated power systems, focusing on the case study of Cyprus.
- Offers insights into the procedures utilized by power system operators in Cyprus for effective and fair RES curtailment implementation.
- Estimates forecasted RES curtailments in Cyprus for 2025–2027 and proposes tailored solutions for mitigating required curtailments.

The rest of the paper is organized as follows: Section 2 demonstrates the need for RES curtailments. Section 3 analyses the historical RES curtailments and presents the forecasted RES curtailments in Cyprus. Section 4 demonstrates the procedures utilized by system operators to curtail energy from RES. Finally, Section 5 provides recommendations for reducing RES curtailments and summarizes the main findings and insights.

2. The need for RES curtailments in Cyprus

In this section, a description of the Cyprus power system is presented, followed by the reasons that force the Cypriot system operators to curtail energy from RES.

2.1. Cyprus power system description

The Cypriot power system is a small and isolated grid with nominal transmission system voltages of 132 kV and 66 kV and frequency of 50 Hz. Currently, there are three major conventional power plants, Vassilikos (VPS), Dhekelia (DPS), and Moni (MPS). The total installed capacity of the generation units is 1478MW which includes 750MW steam turbines (ST), 440MW combined cycle gas turbines (CCGT), 188MW gas turbines (GT) and 100MW internal combustion engines (ICE) [18]. The installed capacity of PV systems is approximately 780 MW (including small roof top and large PV power plants) and 158 MW Wind Power Plants (WPP) (Electricity Authority of Cyprus [[19], 2024]. It is expected that by 2027 the installed PV capacity will exceed 1GW while WPP capacity is expected to remain unchanged [20]. The percentage of electric energy generated from RES in 2024 in Cyprus was approximately 25 %, while the maximum instantaneous RES penetration was 69 % in 2024 (Fig. 1) [21].

The historical maximum demand of the island was approximately 1.3GW, while the minimum demand was 300MW. Peak demand occurred in the summer period due to very high cooling requirements in combination with additional demand from tourism. As can be seen in Fig. 2, for approximately 60 % of the time, the total demand of the system is below 600MW. Currently, there are no large-scale Energy Storage Systems (ESS) installed on the island [21].

All WPPs are connected to the Energy Management System (EMS) of the TSOC, while the DERs above 120 kW are connected to the

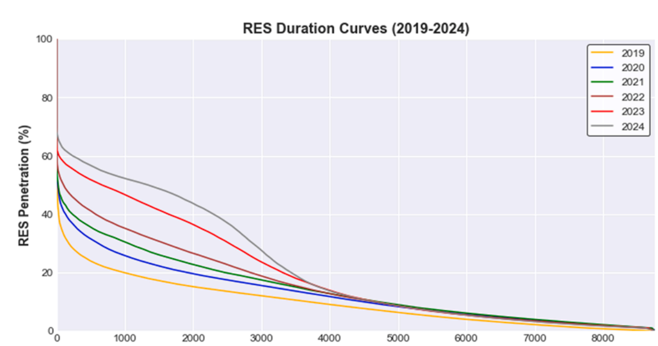

Fig. 1. RES duration curves (2019–2024).

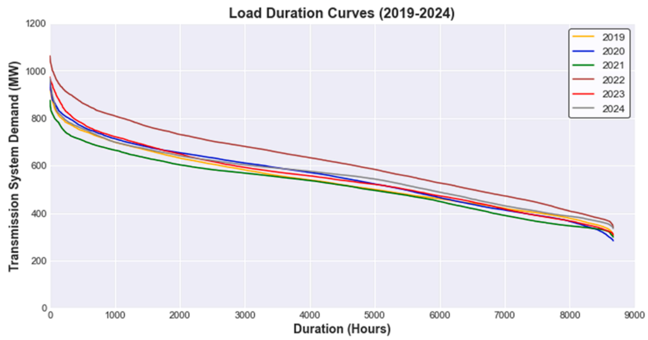

Fig. 2. Load duration curves (2019–2024).

Distribution Management System (DMS) of the DSO. The WPPs and DMS-connected DERs (controllable DERs) can receive active and reactive power set points from the relevant system operator, thus can be actively curtailed [22].

The relatively high-RES penetration compared to the low load demand of the system during certain periods, in combination with the lack of investments for grid reinforcement and flexibility provision requires the extensive use of curtailments to ensure the system's security. Consequently, the power system of Cyprus serves as an ideal case study for evaluating the impact of RES curtailments and exploring potential mitigation strategies.

2.2. Requirements for RES Curtailments

RES curtailments can be manifested either for system wide limitations or local network limitations. In this subsection all the possible reasons for requiring RES curtailment are presented. However, emphasis is given in system constraints which are currently the only requirement for curtailments in the island of Cyprus.

2.2.1. System constraints

RES penetration can impose significant frequency security issues in low-inertia power systems. This is because low-inertia power systems are inherently more vulnerable to frequency disturbances [23]. While RES penetration increases, the large conventional power plants are decommissioned, and the already low inertia of the systems reduces further since DERs do not inherently provide inertia [3]. With the reduction of grid inertia, frequency excursions are faster and more

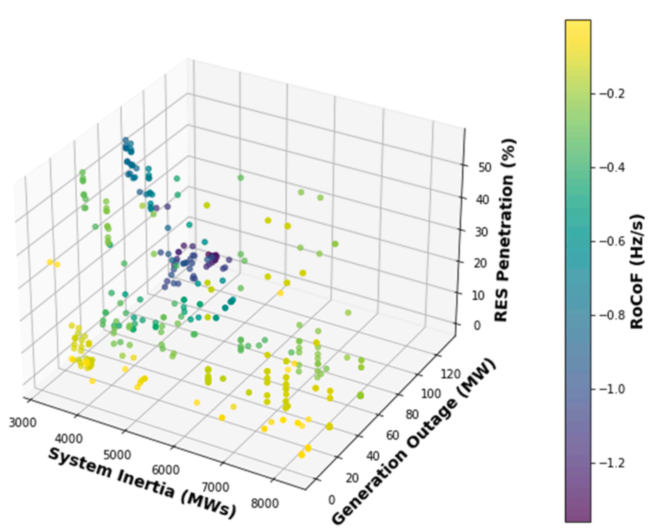

Fig. 3. RoCoF values depending on system inertia, RES penetration, and larger generation outage.

profound, thus increasing the possibility of instability [24,25].

This is demonstrated in Fig. 3, were the Rate of Change of Frequency (RoCoF) values are plotted for different system inertia, conventional generation outages, and RES penetration levels. RoCoF values are higher when the system inertia is lower or when the generation outage is higher. From frequency stability perspective it is vital to maintain RoCoF values above certain limits (usually 1Hz/s).

To ensure that the system can survive credible contingencies, operators of low-inertia power system impose minimum operational requirements. For instance, the TSOs of Ireland and Northern Ireland have set a 75 % limit on the SNSP [17]. Furthermore, they set a minimum requirement of eight synchronized units and a minimum inertia of 23, 000 MWs at any point in time throughout the year [26]. Similarly, the TSOs of Cyprus and South Australia have set a minimum number of four and two synchronized units, respectively [3,27]. These minimum requirements in the number synchronized units (or, equivalently, in minimum inertia) increase the frequency security of the systems. However, the operational security is achieved at the expense of RES curtailments due to the minimum inertia requirements, ramp rate limitations, number of synchronized units, and SNSP.

To better explain this relationship, it should be noted that each synchronized generation unit must operate at least above its Minimum Active Power Generation Limit (MAPGL) due to technical electromechanical constraints. Therefore, by setting a minimum number of synchronized units to be connected to the grid at each point, the total system load supplied by these units must be at least equal to the sum of the MAPGL of all synchronized units. This is depicted as MSGL in Fig. 4 [22]. When the net load demand (defined as total load minus DER generation) is smaller or equal to the MSGL, RES curtailments are initiated as a source of flexibility to balance the system. This situation leading to RES curtailments appears often in islanded systems and further worsens as RES installed capacity is increased.

Furthermore, RES curtailments can occur due to ramp rate limitation of the synchronous generation units. Specifically, as RES penetration increases the net load during mid-day is reduced. However, the evening peak demand remains relatively unchanged especially for PV dominated power systems. Thus, the synchronized units must increase their output power rapidly to satisfy the evening peak demand. Some conventional generation units might not have the required ramp rate capabilities. As a result, energy from RES can be curtailed in order to reduce the maximum required ramp rate. This is depicted in Fig. 5, where energy from RES is curtailed to reduce the ramp rate requirements from 77MW/h to 67MW/h in the penetration scenario P4=35 %. It should be clarified, that in this case RES curtailments are not related to the MSGL. Therefore, even in days with increased demand, RES curtailments can occur depending on the available conventional units.

2.2.2. Local network constraints

RES curtailments can also be applied for local network constraints. These constraints can be related to network congestion and/or voltage issues. Network congestion occurs when RES generation under normal

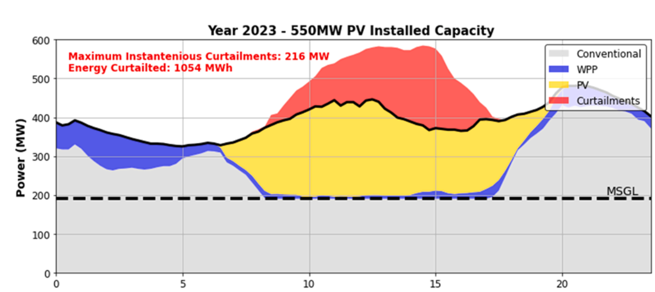

Fig. 4. Generation profile for the lowest load demand day of 2023 (16/4/203) in Cyprus.

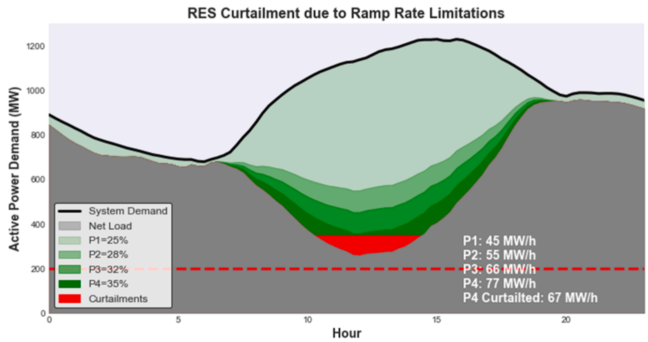

Fig. 5. RES curtailments due to ramp rate limitations.

or contingency conditions exceed the capacity of the equipment. From Fig. 6, which presents the hosting capacity map of the Cyprus power system, it is evident that many large areas of the island have no available hosting capacity [28]. Hosting capacity is the amount of RES systems that can be connected to a part of the power system without violating any operational limits [22]. For the installation of new PV systems in those congested areas, transmission substation upgrades are required. For PV systems with self-consumption (e.g. net billing schemes), PV systems can be connected with zero energy export terms to the grid. Hence, these PV systems are not allowed to inject active power to the grid. These special terms allow the connection of RES systems in congested areas while verifying that the grid will not be overloaded. However, during low self-consumption hours, excessive energy from RES has to be curtailed, since it cannot be exported to the grid.

Moreover, some curtailment can occur due to voltage issues. Recent grid codes require from DERs to limit their active power generated when the voltage at the point of common coupling is above a specific limit [29]. This functionality is known as Volt-Watt or P(U). In this manner, voltages remain within the nominal limits, but some energy from RES can be lost. This functionality has been recently included in the grid code requirements from the Cypriot DSO.

3. Analysis of RES curtailments in Cyprus

3.1. Historical RES curtailments

In this section, the RES curtailments for the years 2022, 2023, and 2024 in Cyprus are presented and analyzed. The total monthly energy generation in Cyprus for the last three years is presented in Fig. 7. The load demand for the island is mainly driven by weather conditions, where the peak energy demands occur in the summer season due to cooling requirements and tourism and semi-high energy demands during the winter season, due to heating needs. In contrast, the load demand and energy consumption are minimized during the fall and spring seasons since both cooling and heating requirements are almost eliminated.

Due to the seasonality exhibited, one can also see the curtailment percentage of the controlled by DMS PV energy generation ranged from 0.1 % to 3.3 % in 2022, from 0.7 % to 19 % in 2023 and from 4 % to 28 %. RES curtailments are maximized during the fall and spring season and minimized during the summer. This happens because there is a substantial difference between the mid-load demands of the seasons. The percentages of the total energy curtailed from RES (over the potential energy generation from RES) were 2 %, 6 %, and 13 % in the years 2022, 2023, and 2024 respectively.

Furthermore, as shown in Fig. 8, only 4 days in 2022 exhibit >200 MWh of daily curtailment, while this number increased to 91 days (a 500 % increase) for 2023, reaching 207 for 2024 (a 100 % increase from 2023). Furthermore, the maximum daily energy curtailment for both WPP and controlled PV was on the order of 600 MWh, while there was no curtailment for 210 days for 2022. For 2023, these numbers changed to 1250 MWh and 105 days, indicating that the curtailment is significantly increasing. Regarding 2024, RES curtailments did not occur in just 53 days of the year, while the maximum daily energy curtailed reached 2145MWh. Results thus show that, from 2022 to 2024, a 100 % annual increase in RES energy curtailed and a 50 % annual decrease in the days where curtailment does not occur, has been documented.

Moreover, the potential generation of electricity from RES and the RES curtailments for the days with the higher percentage of curtailed energy to the energy demand for 2022, 2023, and 2024 respectively are presented in Fig. 9. As can be seen, the energy curtailment increased from 450 MWh on the 7th of May 2022 to 1148 MWh on the 23rd of April 2023, to 1680 MWh on the 1st of April 2024. It is interesting to observe that on the 1st of April 2024, the total production of energy from RES exceeded the energy demand of the whole of the island from 11:15 to 14:45. This phenomenon is expected to increase over the coming years, and even though this wasted energy can be saved, as will be shown in Section 4, a full technoeconomic study needs to be commissioned taking into account the seasonality of the energy demand fluctuations in small islands like Cyprus.

3.2. Forecasted RES curtailments

In this section, daily and yearly RES curtailments for the years 2025,

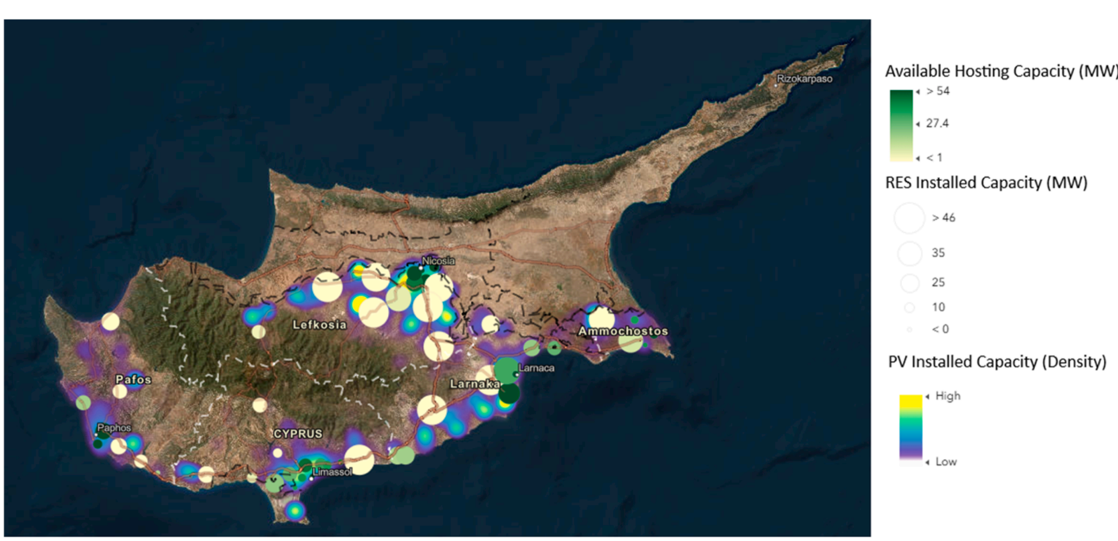

Fig. 6. Cyprus hosting capacity map.

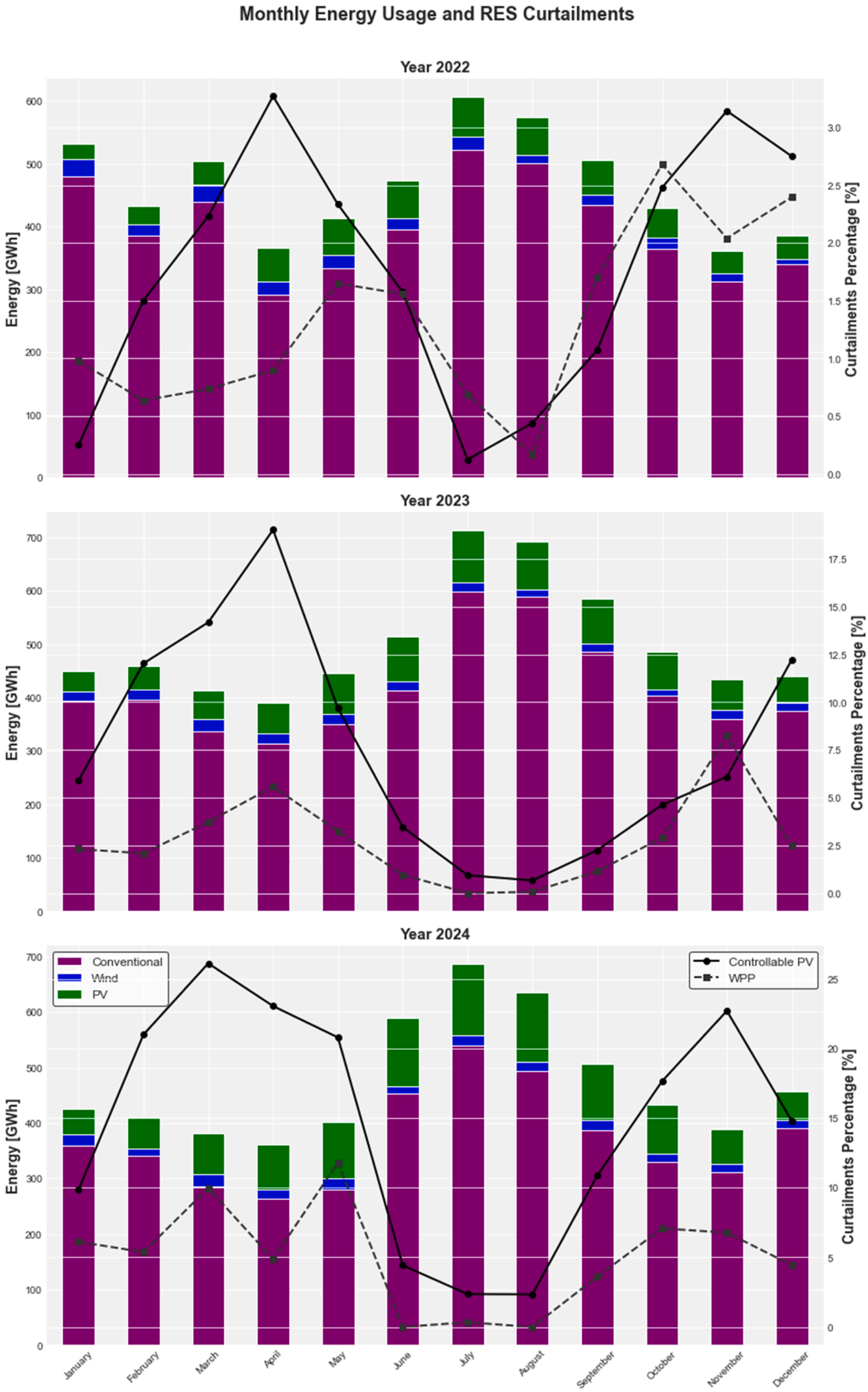

Fig. 7. Monthly generation of electricity in GWh and % of curtailment as a percentage of PV and WPP generation in 2022, 2023 and 2024.

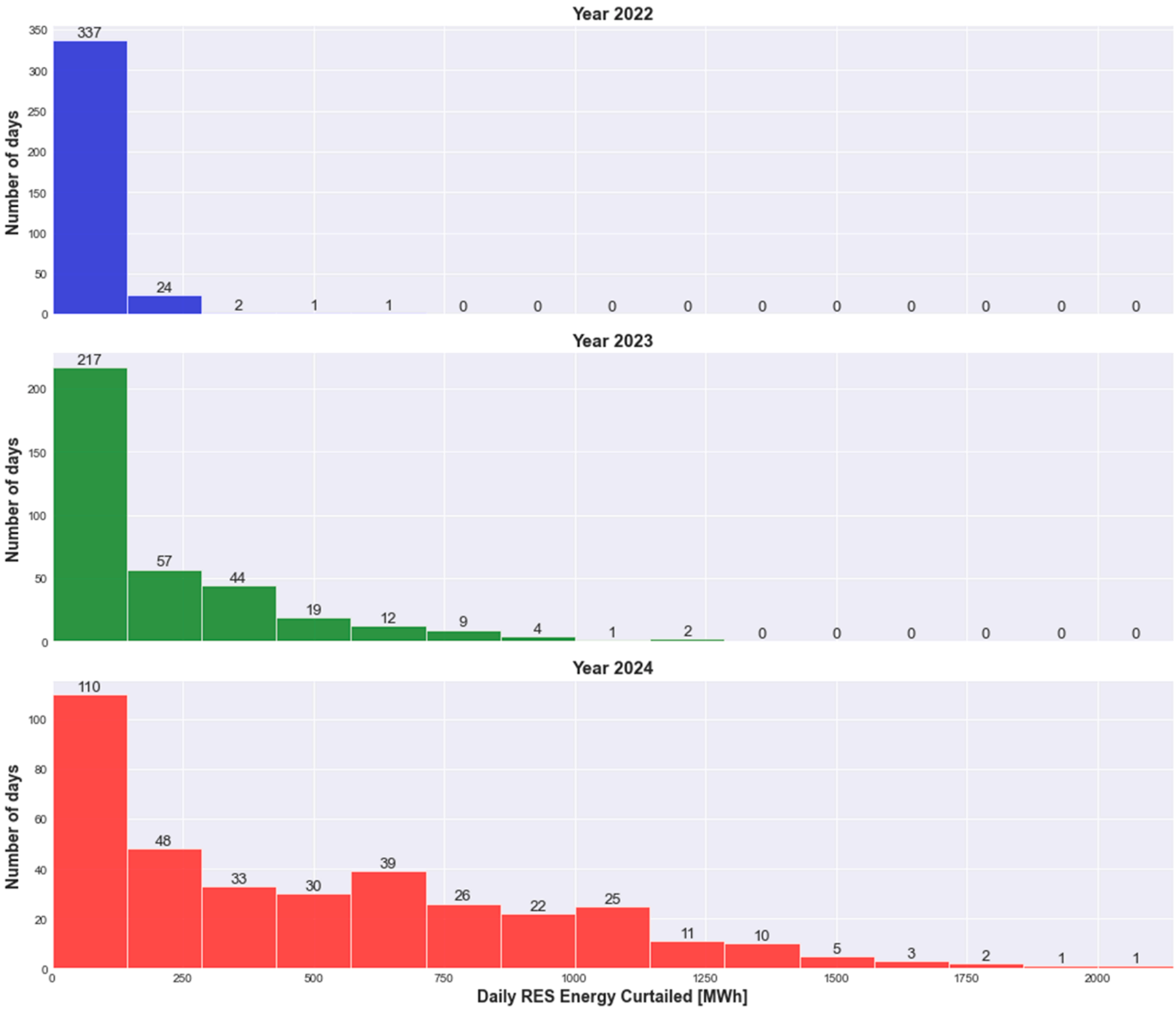

Fig. 8. Histogram of the daily RES curtailment [in MWh] for 2022, 2023 and 2024.

2026 and 2027 are estimated. Initially, curtailments are estimated for three typical days of extremely low demand in spring for each year as shown in Fig. 10. As the installed capacity of PVs increases, the RES curtailments will inevitably increase. This is mainly because the midday demand of the system is not expected to increase at the same rate as PV installed capacity.

Subsequently, the yearly RES curtailments are estimated based on the predicted load demand and RES generation. The load demand is based on historical data from 2022, 2023, and 2024 and the ten-year peak demand prediction of the TSOC [30]. The forecast RES generation is also estimated using historical data and the prediction of the ten-year installed capacity of the Cyprus DSO [20]. The unit commitment (UC) for each day of 2025 is calculated using the proposed UC formulation of [31] and extrapolated for 2026 and 2027. It should be noted that the percentages are estimated based on the total energy generated from the RES. Consequently, the expected RES curtailment for each controllable DER will be significantly higher. From the RES curtailments of Fig. 11, the seasonality of the curtailments maintains the same pattern as in previous years 2022–2024. Furthermore, as already presented in Fig. 10, RES curtailments will be increased since installed capacity of PVs will increase.

4. Curtailments procedures

This section outlines the procedures employed by system operators in the power system of Cyprus to curtail excess energy from RES. An overview is shown in Fig. 12 and the details in Fig. 13. The process begins with the TSOC calculating the required amount of RES curtailments to maintain power system stability. As previously mentioned, RES curtailments are triggered when the net load approaches the MSGL or when ramp rate limitations are exceeded.

Once the need for curtailments is identified, the TSOC initiates the process by curtailing large RES systems connected to the transmission network. Simultaneously, the TSOC requests the DSO to reduce a specific amount of RES generation from large systems connected to its DMS. The DSO calculates and communicates a curtailment factor to each DER. This factor represents a weighted average of the total required curtailments, distributed proportionally based on each system's current active power output. As a result, RES systems with higher generation levels are curtailed more significantly.

Additionally, the DSO instructs RES systems with zero-export contracts to cease exporting energy to the grid. If further curtailments are required after all available energy from SCADA-connected systems has

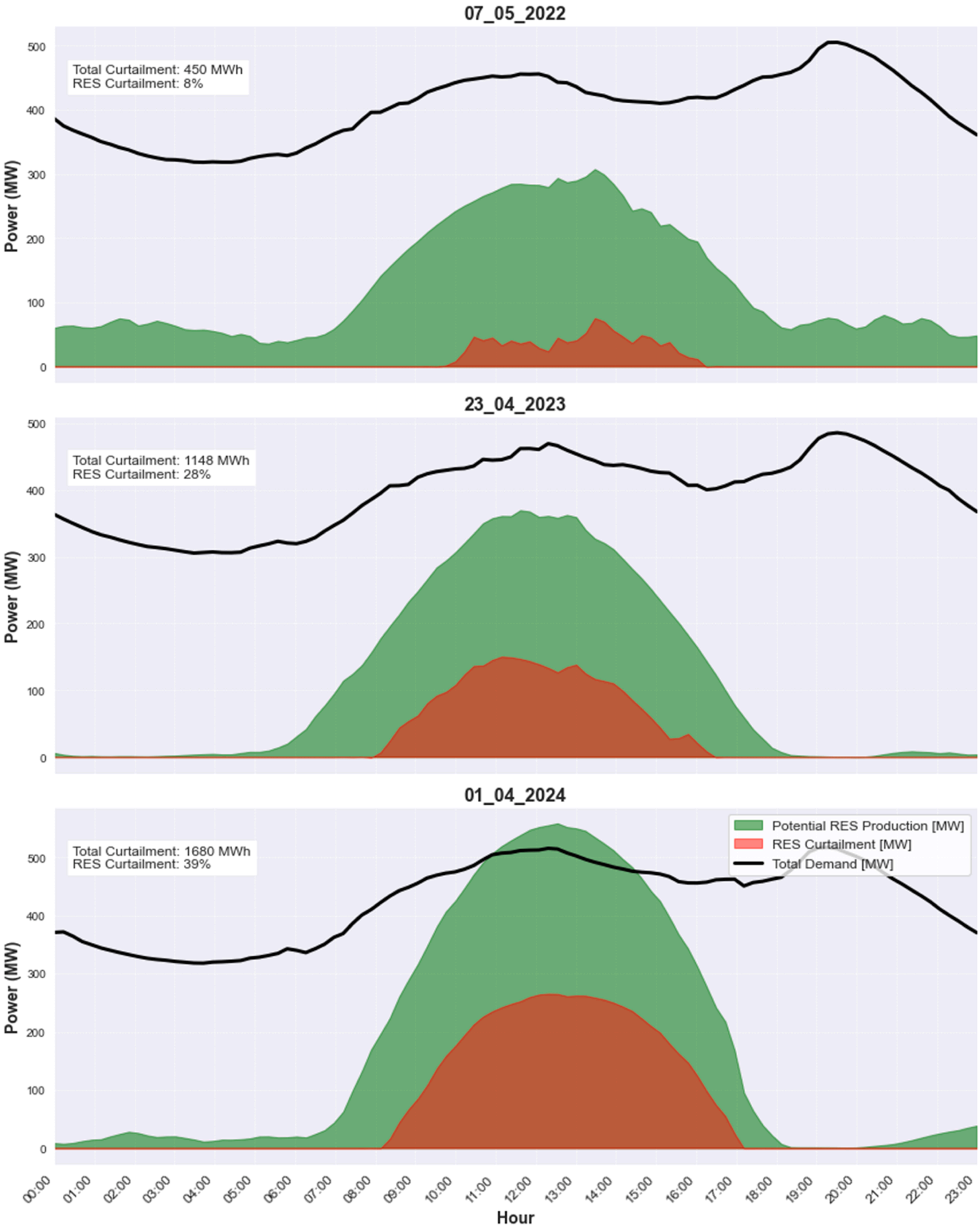

Fig. 9. Hourly RES curtailments for 7/5/2022, 23/4/2023, and 01/04/2024.

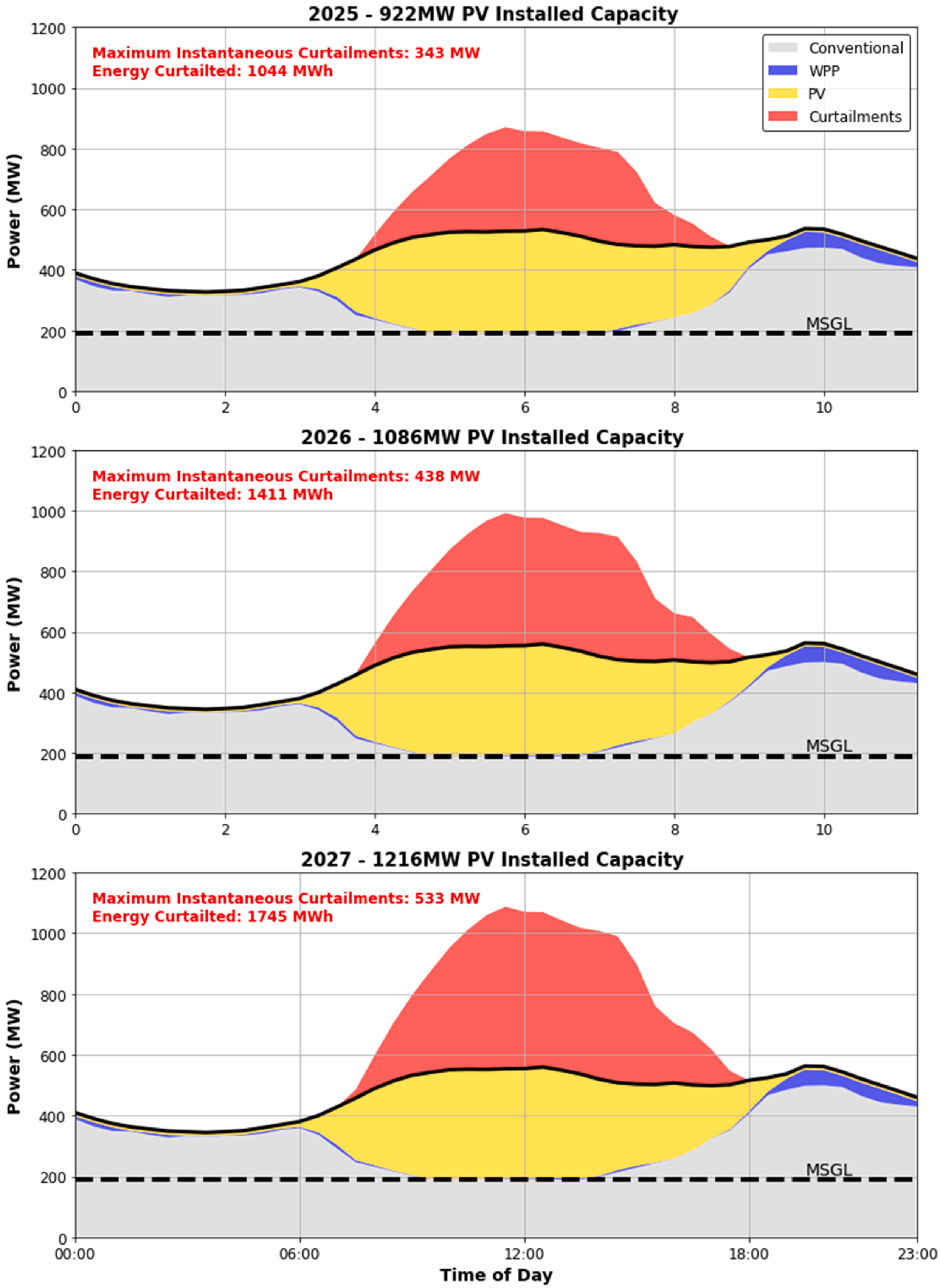

Fig. 10. Forecasted daily generation profiles for typical days in 2025, 2026 and 2027.

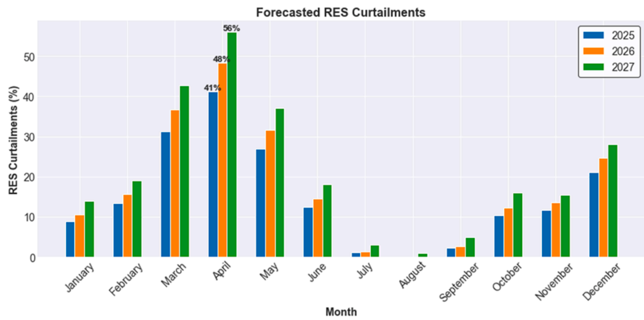

Fig. 11. Forecasted monthly RES curtailments percentages for 2025, 2026 and 2027.

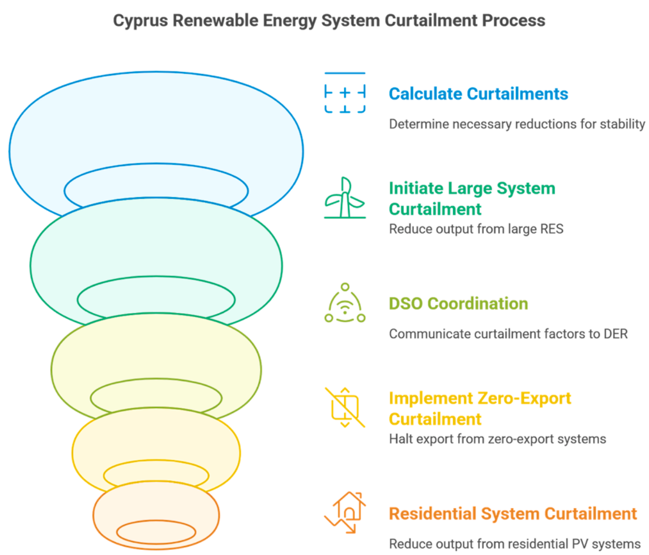

Fig. 12. Overview of curtailment process.

been curtailed, zero-export RES systems are also curtailed. In cases where additional reductions are still necessary, commercial and residential PV systems are curtailed as a last resort. Currently, the DSO can only disconnect DER inverters using ripple control or Internet of Things (IoT) receivers.

As RES curtailments increase, concerns regarding fairness arise. Large PV systems are subject to frequent curtailments, while small residential PV systems are typically disconnected only a few days per year. To address these fairness concerns, the DSO has established a priority list for curtailments, as shown in Table 1. This list prioritizes residential PV systems as the last line of defense, whereas large PV systems have the highest curtailment priority. Efforts are also made to ensure equitable treatment across different RES technologies, such as wind power plants (WPPs) and PV systems.

As shown in Table 2, curtailed energy from PV systems has more than double after 2023. This is because WPP have increased generation during the night, when RES curtailment requirements are reduced. During the mid-day, PV generation is maximized and therefore is curtailed. In order to compensate for this significant difference between the two technologies, the TSO could increase the Priority of WPP (EMS Connected). In this manner, WPP should be the first to be curtailed.

4. Solutions for reducing RES curtailments

This section discusses potential solutions for reducing RES curtailments, with a particular focus on analyzing the option of reducing the MSGL of the system through simulations. These solutions aim to enhance the power system's infrastructure and/or provide greater operational flexibility.

4.1. Reducing MSGL

As analyzed in Section 2, it can be concluded that RES curtailments can be significantly reduced by lowering the operational MSGL. This section evaluates the impact of reducing the MSGL on the Cyprus power system. To achieve a lower MSGL, the total number of synchronized generation units must be reduced. However, reducing the MSGL also decreases the system's kinetic energy. The relationship between kinetic energy and the RoCoF is governed by the swing equation. According to this equation, a reduction in kinetic energy results in higher RoCoF values, which may lead to the desynchronization of generation units and potentially cause a blackout [32].

To assess these risks, the frequency response of the Cypriot power system was evaluated for different numbers of generator units at the two major power plants in Cyprus: Vasilikos Power Station (VPS) and Dhekelia Power Station (DPS). Two events were simulated:

- **Event E1**: The outage of a large steam turbine (ST) at VPS at $t = 1s$.
- **Event E2**: The outage of a small steam turbine at DPS at $t = 1s$.

The operating conditions for these simulations were based on the daily demand profile shown in Fig. 4 at 12 p.m. All simulations were performed using DIgSILENT PowerFactory software [33].

The results, shown in Fig. 14, indicate that reducing the number of synchronized units adversely affects the system's frequency response. Specifically:

- RoCoF values increase as total kinetic inertia decreases.
- The frequency nadir declines due to a reduction in frequency containment reserves (FCR).
- Event E1 (the larger event) causes a more significant frequency excursion compared to Event E2.

It is important to note that for Event E1, the scenario with one generation unit at VPS and two units at DPS (1VPS + 2DPS) is not presented because it leads to frequency instability.

4.2. Enhancing power system infrastructure

Interconnections can be used to export excess energy from RES [7]. However, since RES penetration is increasing in most countries, there is a high probability that neighboring power systems will have excess RES generation at the same time. Hence, respective both system operators would like to export their excess power, which is not feasible [34]. AC interconnections can also provide frequency support to the system, potentially reducing the MSGL. On the other hand, HVDC interconnections—necessary for long-distance power transmission—lack the ability to provide grid services such as frequency support.

It should be noted that the maximum import and export capability of an interconnection is limited to maintain RoCoF during N-1 contingency bellow maximum values. Specifically for the power system of Cyprus, and the under investigation Great Sea Interconnector 1GW bipolar HVDC link, it has been calculated that the maximum import or export must be limited up to 600MW to avoid excessive RoCoF values after the outage of one of the two poles of the link.

Installing new generation units with enhanced capabilities can improve the flexibility of the power system. Committing generators with lower Minimum Stable Active Power Generation Levels (MSAPGL) can reduce MSGL and consequently decrease RES curtailments without compromising system stability. Additionally, generators with higher ramp rate capabilities can further reduce curtailments caused by ramp rate limitations [3]. However, this approach reduces the utilization factor of large conventional units, making them economically unviable

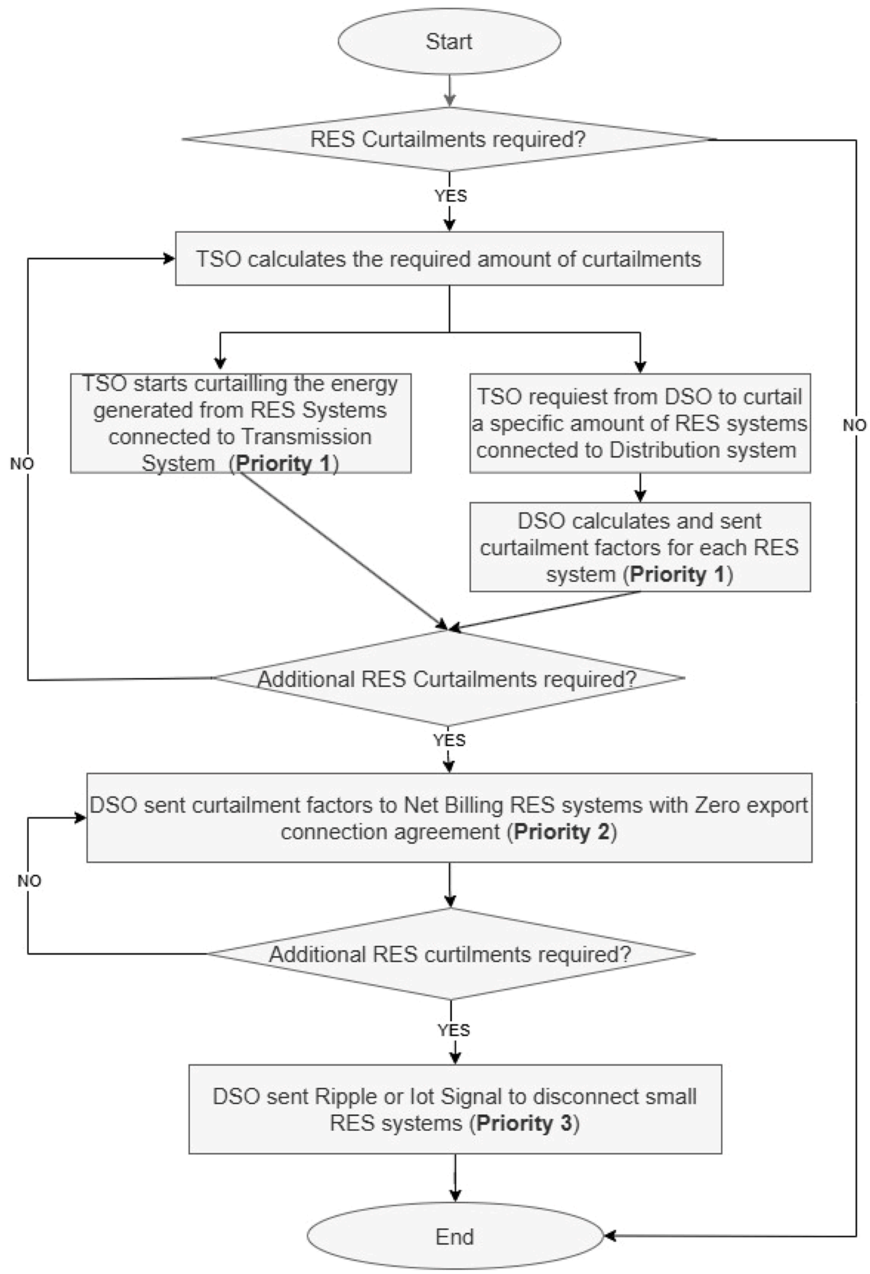

Fig. 13. RES curtailment procedure flowchart.

Table 1
RES curtailments priority list.

Priority	Type	Methodology
1	Large RES systems Connected to Transmission System	Set points from TSOC SCADA system
1	Large RES systems connected to Distribution System	Set points from DSO SCADA system
1	Net Billing with Temporary Zero Export Agreement connected to DSO SCADA	When RES curtailments are initiated a set point from DSO is sent for operation to zero export mode
2	Net Billing with Temporary Zero Export Agreement PV Systems connected to SCADA	Set points from DSO SCADA system
3	Small Residential and Commercial RES systems not connected to SCADA	Ripple or IoT signal for disconnection of a group of RES systems

Table 2
RES Curtailments distribution within RES Technologies.

RES Technology	2022	2023	2024
WPP	1.3 %	2.9 %	5.4 %
PV	1.7 %	6.9 %	13.9 %

and potentially leading to their decommissioning. Such decommissioning could jeopardize system adequacy during periods of high demand.

Furthermore, aging power stations can be retrofitted to operate as synchronous condensers. Synchronous condensers provide both fault current and inertia, which are critical for the secure operation of the power system [35].

4.3. Increasing operational flexibility

ESS can initially be employed to store excess energy from RES and

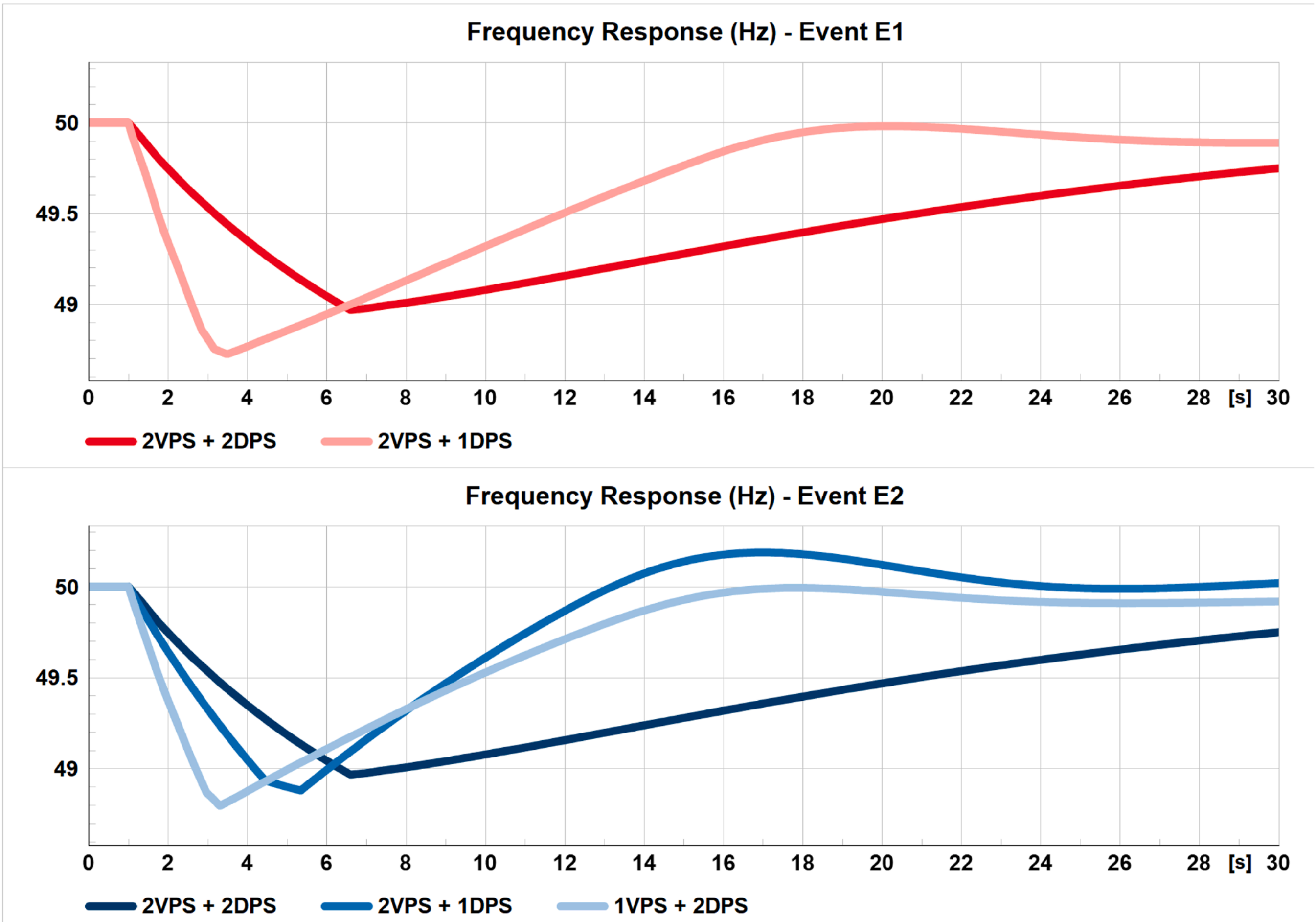

Fig. 14. Frequency response after the outage of a conventional generator with different commitment scenarios.

later export it back to the grid. This functionality helps reduce RES curtailments caused by violations of the MSGL or ramp rate requirements, particularly during late afternoon hours. Additionally, ESS with grid-forming capabilities can provide virtual inertia to the system [36]. By doing so, the MSGL can be lowered, further reducing RES curtailments.

For the power system of Cyprus, the Transmission System Operator of Cyprus (TSOC) has estimated that an ESS capacity of 80 MW with 240 MWh is required to maintain RES curtailments below 10 % by 2025. To achieve a further reduction below 6 %, the ESS requirements increase to 200 MW/400 MWh. A recent study [37] calculated that achieving a 50 % annual RES penetration by 2032 would require an installed ESS capacity of 850 MW/4250 MWh.

In addition to ESS, demand-side management can also help reduce RES curtailments. Flexible loads can be shifted or activated during midday hours when curtailments are typically at their peak. However, this solution may be less effective for small power systems with low total load demand. This limitation arises because only a small portion of the load demand—such as white appliances—is flexible, while the majority remains inelastic [38]. However Electric Vehicles (EVs), present a promising alternative for small power systems. EVs can increase overall system demand if their charging patterns are made elastic to market signals or controlled centrally. To encourage this behavior, economic incentives such as time-of-use tariffs should be offered to EV owners to promote charging during periods of excess RES generation [39].

Advanced forecasting tools also play a critical role in mitigating RES curtailments by reducing operational uncertainty. The use of artificial intelligence (AI) methods has significantly improved the accuracy of forecasting tools [40]. More accurate predictions of RES generation enable more optimal unit commitments with fewer constraints while maintaining high system security. A combination of improved forecasting and ESS deployment has been found highly effective in reducing RES curtailments in isolated power systems [41].

While infrastructure investments are effective in addressing the RES curtailment challenge, solutions based on operational flexibility are often less costly, more scalable, and capable of being implemented incrementally. Ultimately, a combination of solutions tailored to the technical requirements and specific characteristics of each power system offers the most economical and secure approach to addressing this issue (Fig. 15).

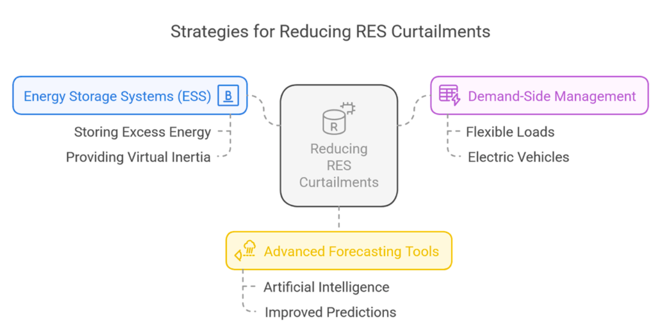

Fig. 15. Solutions for increasing operational flexibility to reduce RES curtailment.

5. Conclusion

The massive penetration of RES in small, isolated power systems without adequate flexibility resources inevitably leads to high levels of curtailment to ensure system security. This is evident from the experience of the islanded power system of Cyprus. As demonstrated in Section 3, increasing the installed RES capacity on the island will not effectively raise RES penetration, as nearly all additional RES generation will be curtailed. This results in significant revenue losses for WPP and PV park owners, and hinders the achievement of national targets for RES penetration and greenhouse gas emissions reduction.

Due to the seasonal variations in energy demand in Cyprus and the rapid growth of RES integration into the grid, the percentage of curtailed PV energy generation controlled by the DMS increased from 2 % to 13 % of total energy demand between 2022 and 2024. Additionally, the number of days with no curtailment decreased from 210 to 53 days during this period. Simulations indicate that these figures will worsen over the next three years. To effectively increase RES penetration while maintaining secure power system operation, solutions that enhance infrastructure, improve operational flexibility, and reduce system uncertainty must be implemented. A combination of infrastructure-based and operational solutions is essential to provide the flexibility required to keep RES curtailments within acceptable limits. Such a multi-faceted approach is the most feasible and effective method for securely achieving high levels of RES penetration.

Power systems with characteristics similar to those of Cyprus must be prepared to address the challenges associated with increased RES penetration. Fairness among different types of RES owners and technologies should be a key consideration. System operators must develop transparent and publicly available procedures to ensure equitable treatment.

If infrastructure enhancements or operational flexibility solutions are not implemented in a timely manner, having control over DERs and reducing their generation becomes a critical functionality for system operators. Therefore, provisions should be made, and minimum technical requirements for DERs should be established to ensure that most DERs are controllable and can be curtailed when necessary. This measure should serve as a temporary security solution until more effective long-term measures are implemented.

CRediT authorship contribution statement

P. Therapontos: Writing – original draft, Investigation. **R. Tapakis:** Writing – original draft, Investigation. **P. Aristidou:** Writing – review & editing, Supervision, Methodology. **A.G. Charalambides:** Writing – review & editing, Supervision, Methodology, Conceptualization.

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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