# Increasing RES Penetration in the Cyprus Power System: Current and Future Challenges

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## Abstract

In recent years, the islanded electric power system of Cyprus is facing significant challenges. The increased penetration of Renewable Energy Sources (RES) in combination with the reduced reliance on conventional generators and the changes in the consumption profiles, lead to a plethora of problems widely related to low-inertia grids. These challenges vary during the different seasons of the year, due to different demand and generation conditions. Several security problems related to frequency, voltage, and fault levels are already observed in the system. The scheduled future increase of RES penetration will lead to deterioration of the system security – if adequate measures are not taken. In this paper, we present the existing problems observed in the Cyprus power system along with an overview of the expected problems due to future RES levels. Finally, we briefly discuss solution mechanisms.

## 1 Introduction

Aiming to make Europe the first carbon-neutral continent by 2050, European Commission (EC) has recently published the 'Fit for 55' package. This package is a set of proposals that each country Member State should follow to reduce greenhouse gas emissions by 55 % until 2030 [1]. In addition to that, due to the current geopolitical situation in East Europe, EC has recently presented 'REPowerEu' plan in order to reduce the dependency of Europe on Russian imports. This can be achieved by accelerating even further RES penetration, energy savings, and diversifying energy sources [2].

The Mediterranean island of Cyprus has managed to achieve part of its targets by reaching 14.9% in 2021 for the energy generated by RES over the total electricity demand [3]. The current target for RES share in gross final electricity consumption is 26 % for 2030 [4]. However, this will probably be increased to 32 % to satisfy the new EC ambitious targets.

Accelerating green energy transitions through massive RES penetration has already imposed significant challenges to many power systems worldwide and led to multiple events. In 2018, a large voltage disturbance occurred in the Tasmanian network due to the disconnection of a reactive plant [5]. It was concluded that the network was weak due to the decommissioning of synchronous power stations replaced by RES. Similar voltage issues, that can potentially lead to voltage instability, have been observed in the Australian network [5].

At the same time, National grid, the UK Transmission System Operator (TSO), has estimated that the transmission system fault levels are reducing because of the increased RES penetration. It has been estimated that the short-circuit level will fall below 12.5kA for more than 50% of the time in 2027 compared to 17.5kA in 2018 in some areas of the 400 kV transmission network. This could impose similar challenges as the Australian and Tasmanian power systems [6]. In addition to that, in August 2019 in the UK, more than one million customers were disconnected due to high rate of change of frequency (RoCoF) values that activated the loss of mains protection of distributed generation [7].

In 2018, a black-out occurred on the Hokkaido island of Japan due to an earthquake. It was estimated that the decrease in system inertia, caused by the decrease of synchronized generators due to the increased RES penetration, had influenced the frequency response of the system during the event [8]. Also, even though there is a noticeable installed capacity of pumped-storage hydropower in Japan, which add flexibility to the power system, RES curtailments occur regularly during low demand periods [9].

In the All-Island area of Ireland, the TSOs SONI and EirGrid have projected that their ambition for 70% RES penetration by 2030 cannot be achieved without significant network reinforcements. Due to the already massive penetration of RES on the island of Ireland, some major operation requirements have been established to maintain frequency stability [10]. These are related to maintaining minimum inertia, maximum RoCoF, a minimum number of synchronised units, and minimum frequency containment reserve requirements (FCR). Additional RES penetration is anticipated to increase the largest single infeed (LSI), that is the maximum generation that might be lost during a single element outage. As a result, the system will be exposed to more severe under-frequency events. Finally, Ireland has been experiencing low-frequency oscillations which can impact the system stability and are enhanced during low-inertia conditions [10].

In general, different power systems face different challenges due to RES penetration [11]. Small islanded systems,

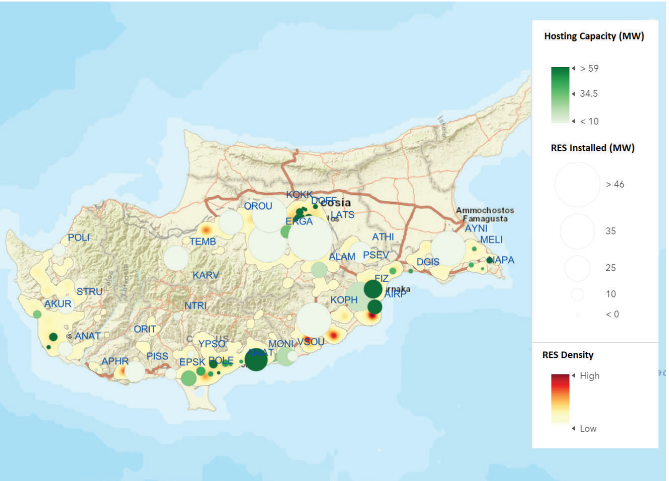


Fig. 1: Cyprus RES installed and hosting capacity in May 2022

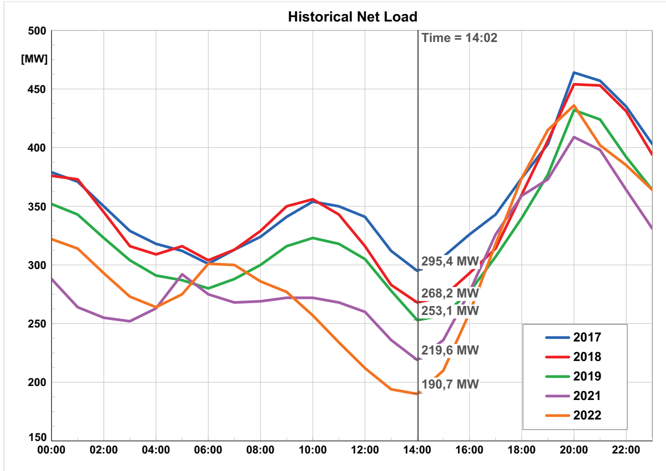


Fig. 2: Historically minimum net loads 2017-2022 (Easter Sunday of each year)

like Hawai, have significant frequency and control stability issues due to low inertia and reduced short-circuit contribution. Medium islanded systems, such as Ireland, may experience frequency stability issues that can be further enhanced by wide-area low voltage propagation phenomena during faults. In large islanded systems, like Texas, voltage stability and system strength is also a challenge since RES are located far from load centres.

In this paper, we present the current and upcoming challenges identified in the islanded electric power system of Cyprus due to the rapid increase in RES penetration leading to extremely low-inertia conditions. We first define realistic future scenarios based on current trends and national policies that are then analyzed concerning issues related to congestion, frequency and voltage stability, and system strength.

The rest of the paper is organized as follows. In Section 2, basic information on the Cypriot Power System (CPS) is presented. In Section 3, the current and future challenges of the CPS are analyzed and discussed. The future needs of the CPS are briefly presented in Section 4. Finally, Section 5 summarizes the main findings and insights.

## 2 Power System of Cyprus

The CPS has many unique characteristics attributed to its small size and the fact that it does not have any interconnection with other power systems. The nominal system voltage of the transmissions system is 132 kV and 66 kV and the frequency is 50 Hz. There are 60 HV/MV transmission substations. The total installed capacity of conventional generation is 1478 MW which is installed in the three power stations at Vasilikos (VPS), Dhekelia (DPS) and Moni (MPS). There are currently 325 MW installed capacity of PhotoVoltaic Plants (PVP) and 158 MW of Wind Power Plants (WPP). It is estimated that the PVP installed capacity will increase to 1000 MW while WPPs up to 200 MW by 2030 [3]. Figure 1 shows the location and size of the current RES capacity as well as the hosting capacity of each HV/MV transmission substation [3].

Currently, approximately 70% of the time, the total demand of the system is below 630 MW while the maximum historical demand of the power system was 1236 MW (recorded in 2021). The maximum demand is anticipated to reach 1390 MW by 2030 [12]. The historically lower net load demand, which is the amount of power that is generated by conventional generators, from 2017 to 2022 is presented in Fig. 2. It can be clearly seen that the net load has been reducing during the mid-day, creating the well-known "duck curve". This is due to the fact that during these hours, PV generation is at maximum, thus the amount of load satisfied by conventional units is reduced.

All distributed energy resources (DERs) in Cyprus are operating based on the national grid code which is mainly inspired by the German Standard VDE 4105. The most important requirements imposed on DERs are i) Over-frequency active power reduction; ii) Low-voltage ride-through capability (LVRT); and, iii) Reactive power absorbing based on $cos\phi(P)$ curve during steady-state conditions [13]. It should be noted that the requirement parameters vary according to the size of the DER installed capacity.

Similarly, with most European system operators, both the transmission system operator of Cyprus (TSOC) and the distribution system operator of Cyprus (DSO) are not allowed to own or operate energy storage systems (ESS). Consequently, there currently are no ESS installed on the island, with the exception of some small residential units and a 1 MW pilot installation. The legislation has recently changed to allow for private investments in ESS with the appropriate mechanisms to participate in the market, however, none have been implemented yet.

## 3 Challenges

This section introduces the challenges identified in the CPS.

### 3.1 *Operation During Low Load Conditions*

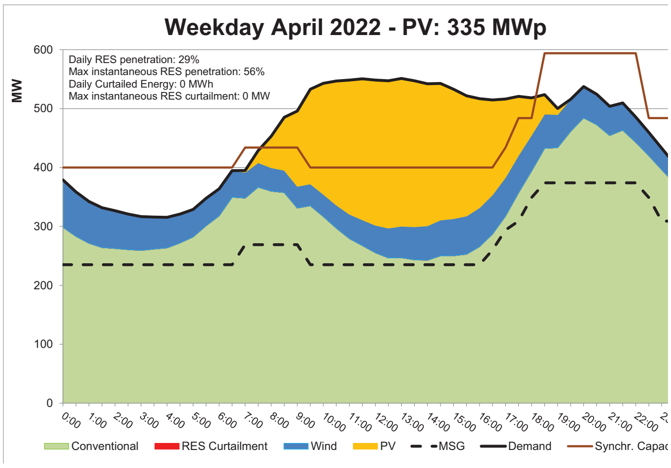
The CPS faces critical challenges during low load conditions that occur mainly in Autumn and Spring. During these months, the total system load is at the lowest as heating and cooling requirements are negligible. In addition, PVPs are more efficient compared to the summer period due to the lower ambient temperatures. As a result, PV generation is maximized which causes the net load of the system to be extremely low (see Fig. 2).

Simultaneously, it has been calculated by the TSOC that conventional generators with an approximate capacity of 200 MW need to be always online to provide the necessary inertia and support the system during faults. The Minimum Stable Generation Limit (MSGL) of the committed conventional generators is one of the major reasons that lead to RES curtailments in Cyprus. Another major reason relates to the ramp-rate constraints of the conventional generators. As can be seen in Fig. 3, when the net load (provided by conventional generators) is below the MSGL (black dashed line), RES curtailments occur. If RES penetration keeps increasing while demand remains unchanged and no mitigation actions are taken, then the amount of curtailed RES energy will also increase.

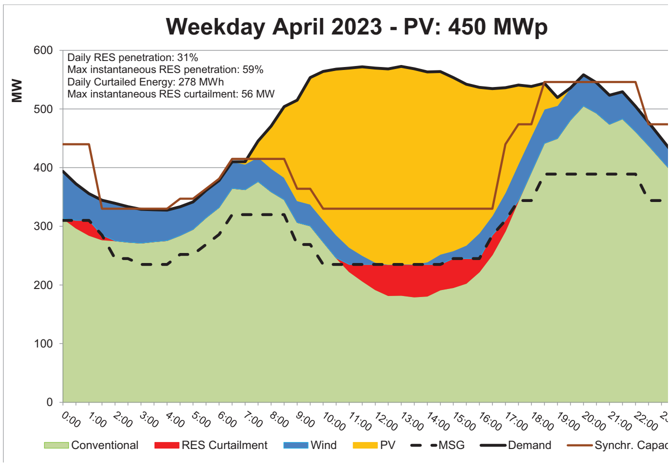
The expected future RES curtailments for the years 2023 and 2024, based on predicted system load and RES generation curves, are demonstrated in Figs. 3b and 3c. It is shown that the amount of RES energy curtailed is anticipated to increase due to the estimated additional 265 MW of PVP capacity expected to be installed by the end of 2024. It should be noted that these predictions are for a common weekday in spring, thus the expected curtailments during the weekends (or holidays) will be significantly higher as the demand will be reduced.

In the CPS, the capability for remote curtailment is currently only mandatory for DERs with an installed capacity higher than 7.14 kW. Consequently, all DERs with lower installed capacity, mostly small-scale residential PVPs, are uncontrolled. In extremely low-demand conditions, the CPS stability can be jeopardized if further generation curtailments are necessary but not available. Currently, the installed capacity of uncontrolled DERs is approximately 100 MW. The maximum allowed installed capacity of uncontrolled DERs estimated by the TSOC in 2021, based on projections of the minimum demand in 2025, is 240 MW.

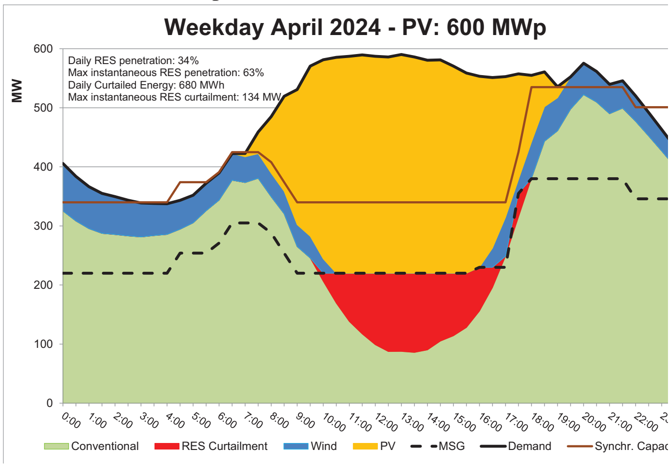
Further reduction of RES energy curtailments without mitigating actions(such as installation of ESS), can be achieved by either reducing the MSGL or with the commitment of more flexible conventional generation units with lower MSGL and higher ramp rates. The latter solution is technically not possible due to restrictions in the current CPS generation portfolio.




(a) Current RES curtailments (2022)




(b) Expected RES curtailments (2023)




(c) Expected RES curtailments (2024)

Fig. 3: Expected RES curtailments during a Weekday in Spring

#### 3.1.1 *Frequency Response:*

In this subsection, we evaluate how the CPS response is affected when the MSGL is reduced by reducing the minimum required number of synchronised conventional units. Initially, the frequency stability of the CPS is evaluated for three different Unit Commitment (UC) and Economic dispatch (ED) scenarios referring to gradually reduced MSGLs, as presented in Table 1. The operating conditions from the lower demand of 2021 have been used as a reference for all three scenarios. This refers to a total system demand of 415 MW from which 203 MW were generated from conventional generation units while the additional 211 MW were generated from RES. The event simulated in each scenario is the loss of the larger connected generator (Steam Turbine (ST)

Table 1 Scenarios description

| SCENARIO | SC1 | | SC2 | | SC3 | |
|---|---|---|---|---|---|---|
| **Generation [MW]** | **UC** | **ED** | **UC** | **ED** | **UC** | **ED** |
| Steam Turbine VPS | 2X120 | 60 | 2X120 | 60 | 1X120 | 60 |
| Steam Turbine DPS | 2X60 | 30 | 1X60 | 30 | 2X60 | 30 |
| PV | N/A | 140 | N/A | 170 | N/A | 200 |
| WPP | N/A | 40 | N/A | 40 | N/A | 40 |
| **RES Penetration** | **31%** | | **34%** | | **35%** | |
| **RES Curtailed [MWh]** | **607** | | **381** | | **217** | |
| **$E_{kin,sys}$ [MWs]** | **2665** | | **2177** | | **1820** | |

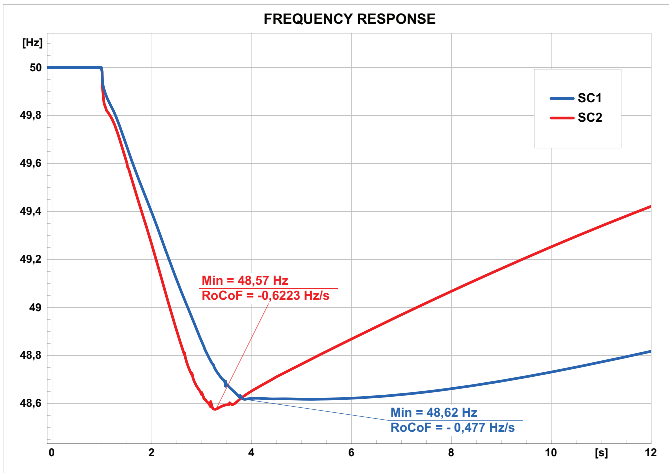



Fig. 4: Frequency response for different scenarios (SC3 is unstable and not shown)

at VPS) at $t = 1$ s. All simulations have been performed using DIgSILENT PowerFactory [14].

The frequency response for Scenarios 1 and 2 are presented in Fig. 4. In SC2 there is only one generator connected to DPS, frequency nadir is lower, and RoCoF is higher. This is due to the fact that the system inertia, as well as spinning reserve and FCRs, are reduced. It should be mentioned that in SC3, where there is only one generation unit in VPS, the CPS becomes unstable after the event, so it is not shown.

Despite the fact that in SC2 stability is maintained after the event, reducing the MSGL must be further examined to include ramp-rate and system strength requirements. Also, it should be mentioned that in SC1 frequency stability is maintained even in a cascading event (N-2), where two generators (one ST in VPS and one ST in DPS) are disconnected while in SC2 stability is lost.

*3.1.2 System Strength:* To examine the impact of reducing MSGL on the CPS strength, a short-circuit analysis has been performed. Short-circuit levels are well-known indicators and the analysis has been performed on twelve 132 kV busbars of important substations. The twelve substations have been selected based on their fault impedance and the total amount of RES and conventional generation connected to them. For evaluating the short-circuit levels, the "Complete Method" available in DIgSILENT PowerFactory has been used for a three-phase zero-impedance fault.

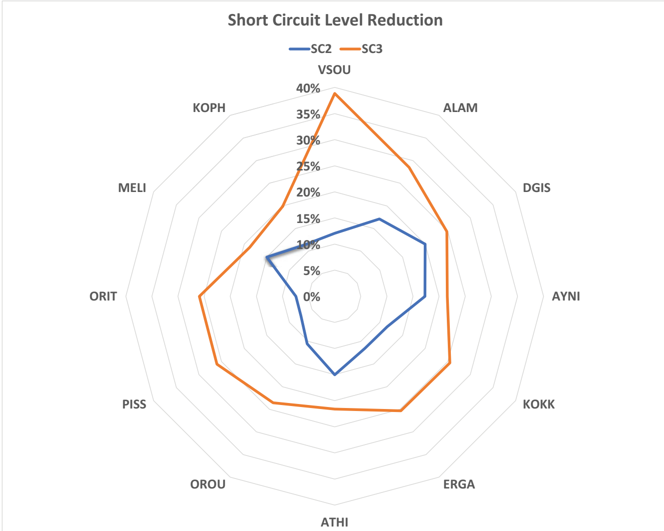



Fig. 5: Short circuit level reduction for scenarios SC2 and SC3

Figure 5 shows the fault level reduction for scenarios SC2 and SC3 compared to SC1. The reduction is more evident in substations VSOU and DGIS which are close to the conventional power stations. On the other hand, in the remote substations of MELI and ORIT the fault level reduction is minimal since the system impedance has a profound impact on fault levels.

As detailed in the literature, the reduction of system fault levels can have a noticeable impact on the power system dynamic performance and protection, especially during voltage events. Such events can lead to abnormally low voltages and trigger the cascaded disconnection of DERs [5] [11]. In massive penetration scenarios, the loss can lead to the need for partial load shedding or even black-out. Recently due to a delayed fault clearing in a transmission line in CPS, approximately 30 MW of DERs were disconnected due to under-voltage protection. It has been estimated by the DSO, that if either the fault clearing times were smaller, the DERs had LVRT capabilities or the system fault levels were higher DERs would have remained connected.

### *3.2 Operation During Medium and High Loading Conditions*

During higher loading conditions, above 600 MW, the aforementioned challenges are mitigated. Specifically, with the current RES penetration levels, the generation from the synchronised units is necessarily more than the MSGL to satisfy the increased demand. Consequently, frequency stability issues and RES curtailments are practically eliminated. In addition, fault levels are higher due to the number of conventional generation units synchronised. Higher RES penetration during the Summer (high loading conditions) is beneficial for the system operation since the peak PV generation is coincident with the peak load demand, thus synchronization of additional units to satisfy the maximum demand is usually avoided. However, some new challenges do exist during medium and high loading conditions as detailed below.

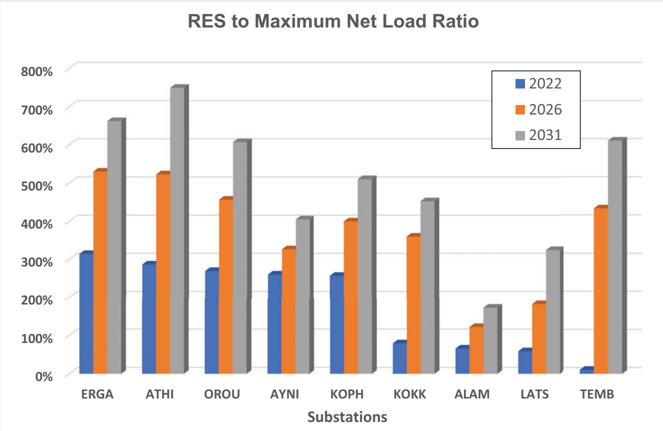



Fig. 6: RES to maximum net load ratio on selected substations

*3.2.1 Network Congestion:* During medium loading conditions, which mainly occur in Winter daylight hours, the total system demand is within the range of 600 to 750 MW and the RES curtailments are negligible. However, the increased RES penetration can lead some parts of the network to become congested due to reverse power flows. This occurs because RES systems and especially PVPs are usually connected in rural areas where the demand is low. Based on the current distribution of the PVPs in the CPS (see Fig. 1), it is observed that more than 50% of the total PVP capacity is installed on nine transmission substations. The installed RES capacity to maximum expected load ratio on these substations is presented in Fig. 6. It can be seen that the ratio is very high on these substations and is expected to dramatically increase in 2026 and 2031. This massive RES penetration will unavoidably cause many transmission substations and lines to be overloaded during normal or contingency scenarios.

Therefore, a contingency analysis has been performed to identify the number of transmission lines and substations that would be overloaded based on the future RES and maximum load projections. It should be noted that for this analysis the transmission system of Cyprus was modelled based on the ten-year development plan of the TSOC. Therefore, all planned upgrades/reinforcements of the transmission system have been incorporated. As shown in Table 2, different system demands and RES generations have been used in the analysis that represents realistic medium to high demand conditions for each reference year. The contingency analysis function of DIgSILENT PowerFactory was used. Only the N-1 criterion has been applied and the results are summarized in Table 2.

In this table, it can be clearly seen that the number of congested transmission substations is increasing. For the transmission lines, only one transmission line violation is expected after 2026. It is noted that during summer periods with high loading conditions, the number of elements congested will be lowered than those estimated with contingency analysis as system load is increased (high cooling requirements) and reverse power flow is reduced.

Table 2 N-1 Contingency analysis results

| **Year** | 2022 | 2026 | 2031 |
|---|---|---|---|
| **System Load (MW)** | 800 | 900 | 1000 |
| **RES Generation (MW)** | 300 | 600 | 750 |
| Lines with Loading 80-100% | 1 | 1 | 1 |
| Lines with Violations (>100%) | 0 | 1 | 1 |
| Transmission Substations with Loading 80-100% | 4 | 1 | 2 |
| Transmission Substations with Violations (>100%) | 1 | 7 | 9 |

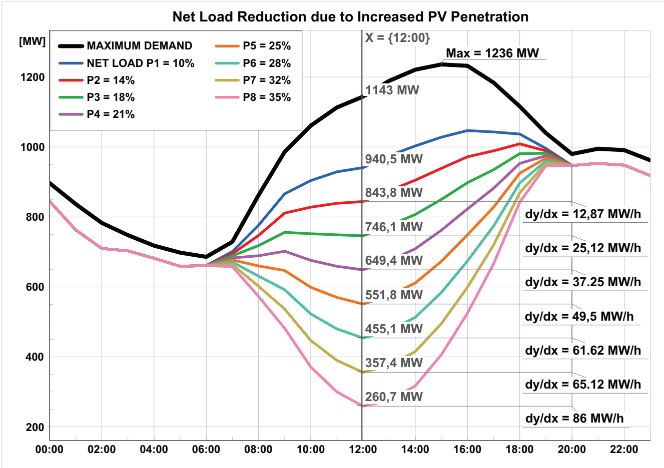



Fig. 7: Net load reduction due to increased RES penetration during high loading conditions

*3.2.2 Ramp Rate:* During high loading conditions, in combination with massive RES penetration, the ramp-rate constraints (maximum rates that generation units can increase or decrease their active power outputs) will be increased. This is due to the fact that increased PV generation during mid-day will significantly reduce the mid-day net load, while the afternoon peak demand remains the same, as shown in Fig. 7 for different penetration levels. At first, the load profile of the historically highest peak demand of the system (August 2021) was used. Afterwards, the generation from PVPs was increased in steps, and different net load demand curves were constructed. It is shown that while RES penetration increases, ramp rate requirements are significantly increased.

*3.2.3 Generation Adequacy:* Finally, generation adequacy issues may occur in the near future during extremely high demands. Currently, RESs are considered to participate, up to some extent, in the energy mix during the system peak demand. However, due to the absence of any large ESS in Cyprus, this cannot be guaranteed. Therefore, there is a noticeable possibility that Cyprus will face some generation shortages in the near future if no mitigation actions are taken.

## 4 Future Needs

From the discussion above, it is evident that the CPS needs significant changes to enable the integration of the expected massive RES penetration in the next decade. As demonstrated, during low load conditions, which account for approximately 40% of the year, further RES penetration will increase energy RES curtailments. Therefore, ESS or more flexible generation units are necessary. In [15], it was estimated that approximately 500 MWh of ESS with a rated power of 450 MW are needed to maintain RES energy curtailments below 1% for PV total installed capacity up to 850 MW. We note that ESS can be beneficial for the CPS operation only if utilised according to the needs of the system operators of Cyprus.

New flexible generation units with low MSGL and high ramp rates, will definitely support further penetration since the issues with MSGL and ramp rates will be mitigated. It should be mentioned that replacing the old conventional generation units with new flexible ones will also maintain the short-circuit levels within adequate limits.

In addition, many transmission substations need to be upgraded in the next years to securely host the expected RES penetration. The upgrade can either be conventional or with non-wire solutions. Conventional reinforcement includes among others installing new or replacing existing power transformers and reconductoring. On the other hand, non-wire solutions include the installation on the MV side of the transmission substation of ESS and dynamic rating solutions. Also, local RES curtailment can be performed during contingencies to avoid overload conditions due to reverse power flows.

While RES penetration increases, it is of paramount importance to ensure that DERs will remain connected to the grid when frequency and/or voltage events occur. Therefore, the grid code requirements must be modified to ensure the proper integration of DERs in the CPS. Some of the possible modifications relate to the LVRT capabilities of DERs with small installed capacity and RoCoF immunity. Furthermore, the ability to receive remote active and reactive power setpoints from the system operators must become mandatory even for small residential PVPs. In this manner, all RES generation could be reduced (curtailed) when system demand is very low. Also, DERs should have advanced grid forming capabilities in order to provide support to the grid during emergencies, similar to those traditionally provided by synchronous generators.

Finally, interconnecting the CPS with neighbouring countries can potentially help to integrate massive RES penetration since excess RES generation, which normally would be curtailed and can be exported. Currently, the development of the "EuroAsia Interconnector" HVDC link is under investigation. This multi-terminal HVDC link will connect the power systems of Israel, Cyprus, and Greece through a submarine cable with a total of 1,208 km in length [16].

## 5 Conclusions

The islanded CPS is currently facing significant challenges due to the increasing RES penetration. These challenges will only become more profound as the target for RES penetration increases in the upcoming years. In this paper, it was demonstrated that the current system cannot accommodate this rate of RES increase without significant changes in the flexibility and strength of the system.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