

Caucasus

Supporting Armenia's Renewable Energy Goals: Data Collection, Validation, and Analysis for the Integration of Autonomous Solar Power Plants in Armenia's Low-Voltage Networks

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Abbreviation	
A	Ampere
ASPP	Autonomous Solar Power Plant
DVC	Dynamic Voltage Control
ENA	“Electric Networks of Armenia” CJSC
kV	kilovolt
kWh	Kilowatt per hour
LV	Low Voltage
MPPT	Maximum Power Point Tracking
MTAI	Ministry of Territorial Administration and Infrastructure of the RA
MW	Megawatt
PCC	Point of Common Coupling
PF	Power factor ($\cos\varphi$)
PSRC	Public Services Regulatory Commission of the RA
RA	Republic of Armenia
SC	Static Voltage Control
SPP	Solar Power Plant
SRIE	“Scientific Research Institute of Energy” CJSC of the RA
WG	The Working Group on “Regulation of problems arising during the operation of solar power plants, including autonomous power generation plants”, formed by order No. 2421-A of MTAI of the RA dated October 11, 2024

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Executive Summary

Since 2018, Armenia has experienced rapid growth in solar power integration into both the transmission and low-voltage (0.38/0.22 kV) distribution networks. This contributes to the strengthening of energy independence; however, it has also led to significant voltage regulation challenges, particularly in low-voltage networks. In certain areas, voltage levels of up to 270–280 V have been recorded, exceeding the long-term permissible range of 198–242 V specified in GOST 32144-2013, *Power Quality Standards in General-Purpose Power Supply Systems*. At the start of this assignment, approximately 35,000 ASPPs with a total installed capacity of about 460 MW were connected to low-voltage networks. This number has since increased to around 50,060 units with the total capacity of approximately 640 MW. This growth has further intensified voltage-related issues.

To address these challenges, SRIE conducted a technical assessment of ASPPs, focusing on inverter voltage and reactive power control capabilities, compliance with operating voltage limits, and the potential for integrating battery energy storage systems. The analysis is based on technical data collected and validated through field inspections, information provided by installers and ENA, and the RA Customs Service data on imported inverter devices for 2018–July 2025. The collected data were digitized and classified by technical characteristics, operational parameters, brands, and manufacturers to support evidence-based conclusions and recommendations.

The assignment was designed to provide an evidence base for addressing voltage quality, inverter functionality, and storage integration challenges associated with the rapid growth of ASPPs in Armenia's low-voltage distribution networks. Under Task 1, SRIE developed the methodological approach, including the sampling framework, data collection templates, and analytical criteria. Under Task 2, SRIE collected, validated, and cross-checked ASPP and inverter data from installers, ENA, MTAI, and field inspections. Under Task 3, SRIE digitized, classified, mapped, and analyzed the collected information, including inverter technical characteristics, geographic distribution, and available Customs Service data on imported inverter devices.

In Task 4, SRIE consolidated, refined, and analyzed the results of Tasks 1–3, with a focus on the technical findings and recommendations needed to support ASPP integration into

Armenia's distribution networks. In particular, the final digitization and systematization of data provided by ASPP installers regarding ASPP installations, as well as data from the RA Customs Service concerning inverter devices, were completed. The collected information was analyzed, and the technical capabilities and parameters of the inverter devices were assessed and grouped according to their technical characteristics and functionalities. The main deliverables include the validated and classified ASPP and inverter datasets, final data sheets and annexes, technical recommendations for voltage control and storage integration, and policy and regulatory insights to support MTAI, PSRC, ENA, and other sector stakeholders.

The SRIE Team also verified installer-provided information through on-site inspections at selected ASPP locations. During these visits, the Team cross-checked inverter parameters, identified any discrepancies between submitted and actual equipment data, and reviewed the overall electrical safety of the installations.

The collected information on grid-connected ASPPs was also corrected and systematized. In particular, the installed capacities of grid-connected ASPPs were grouped according to the number of electrical network branches of ENA and substations to which they are connected. This analysis was carried out based on the information provided by ENA.

Geographical mapping and visualization, particularly the allocation of ASPPs according to their supplying substations, could not be carried out, as ASPPs installation companies do not possess this information. Furthermore, identification in cooperation with ENA was not possible, since the location addresses or customer account numbers are also unavailable.

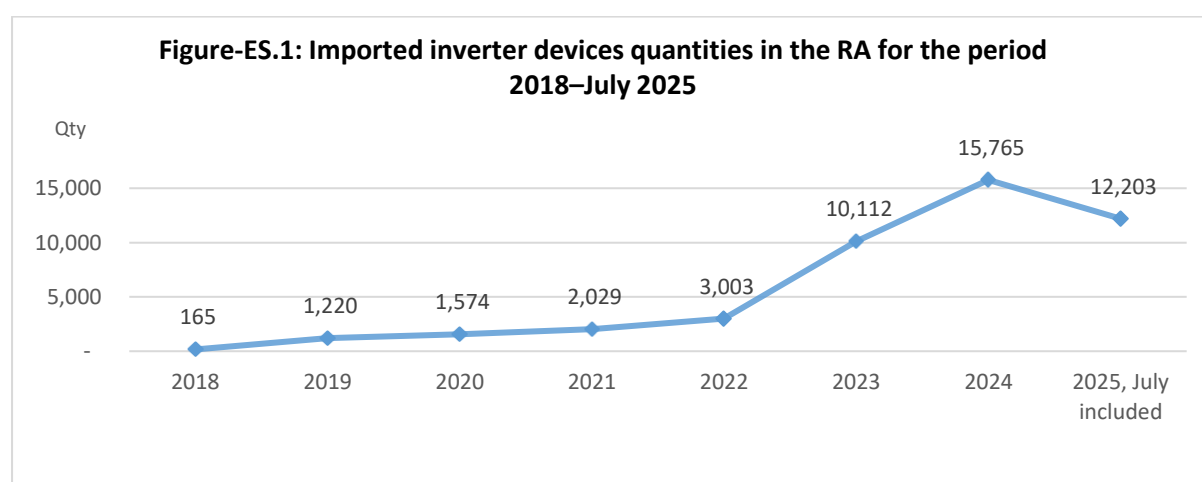
Nevertheless, it should be noted that the absence of this information does not and has not had any negative impact on the accuracy and reliability of the conducted study. This has also been indicated in the reports of the previous tasks.

One of the key issues is the analysis of voltage regimes of grid-connected ASPPs, which depends on several factors, particularly the PCC to the grid, the installed capacity of the ASPPs, the distance from the supplying substation, the density of connections at the PCC, and other parameters. However, this analysis falls outside the scope of the present technical assignment. Nevertheless, it represents a highly valuable and necessary area of study,

which, in our view, should be carried out separately within the framework of a dedicated study.

The final dataset combines three complementary sources of evidence: installer-provided ASPP records, RA Customs Service data on inverter devices imported during 2018–July 2025, and on-site inspection results. Together, these sources support the assessment of inverter voltage control capabilities, storage integration potential, geographic distribution, and electrical safety considerations. The detailed datasets, inspection evidence, technical classifications, and supporting calculations are presented in the Annexes.

As mentioned above, the study of the technical capabilities of inverter devices was also carried out based on information received from the RA Customs Service for the period 2018–July 2025 (see Figure-ES.1).



In total, the RA Customs Service provided information on 46,070 inverter devices for the period mentioned above. However, information on the manufacturer and brand was available for only 44,137 of these devices.

SRIE carried out a comprehensive analysis of the received information, grouped it by inverter device manufacturers and quantities. The total number of the most imported inverter devices in the RA is 43,120, representing 97.695% of the total, as shown in Figure-ES.2, Figure-ES.3.

Figure-ES.2: Total number of the most imported inverter devices to the RA for period 2018-July 2025, %

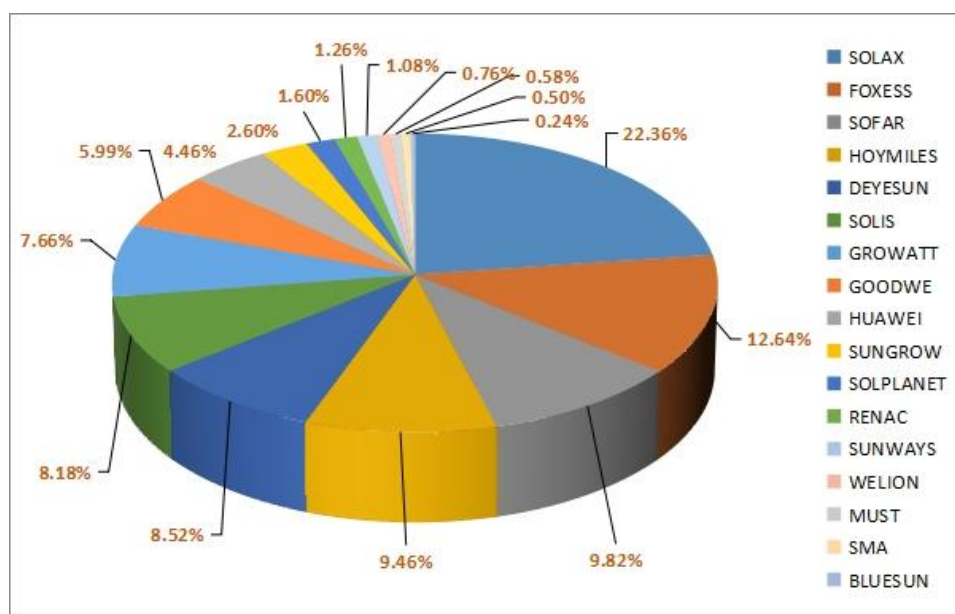
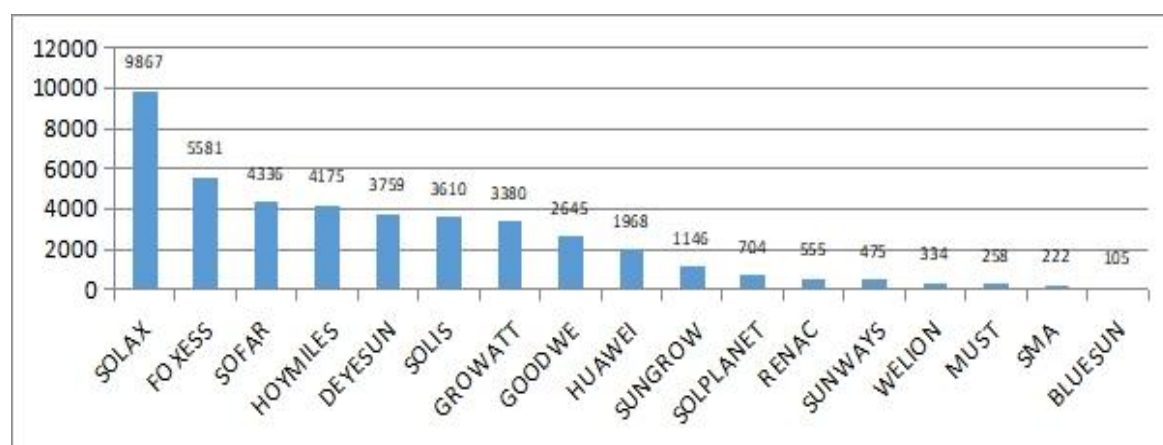


Figure-ES.3: Total number of the most imported inverter devices to the RA for period 2018-July 2025, units



The technical parameters of 400 inverter models from 17 manufacturers were thoroughly analyzed and grouped by manufacturer, brand, and capacity. The results are presented in Annex K.

Manufacturers of inverter devices with dynamic voltage control capabilities are presented in Table-ES.1. Their total number is 41,652 units, representing 94.37%.

Table-ES.1: Manufacturers of Inverter Devices with Dynamic Voltage Control Capabilities

n/n	Manufacturer	%
1	SOLAX	22.36%
2	FOXESS	12.64%

3	SOFAR	9.82%
4	HOYMILES	9.46%
5	DEYESUN	8.52%
6	SOLIS	8.18%
7	GROWATT	7.66%
8	GOODWE	5.99%
9	HUAWEI	4.46%
10	SUNGROW	2.60%
11	SOLPLANET	1.60%
12	SUNWAYS	1.08%

Some inverter models do not explicitly specify dynamic voltage regulation, representing 1,447 units (3.34% of the total). Of these, about 1% have undefined capabilities, while 2.34% are presumed to support dynamic voltage control. Details are provided in Table-ES.2.

Table-ES.2: Manufacturers of Inverter Devices Without Explicit Dynamic Voltage Control Capability			
n/n	Manufacturer	Voltage Control	%
1	RENAC	Presumably (G98, EN 50549, C10/11, CEI 0-21)	1.26%
2	WELION	Undefined	0.76%
3	MUST	Presumably (VDE 4105), partly (depend on model)	0.58%
4	SMA	Static & Dynamic (depend on model)	0.50%
5	BLUESUN	Undefined	0.24%

Taking into account the above - mentioned Table-ES.1 and Table-ES.2 it can be assumed that 94.37 % of the inverter devices imported in the RA have the capability for the dynamic voltage control.

Research was also carried out on the ability of connecting storage batteries to the inverter equipment. As a result, it was clear that nearly 1.59 % (702 units) of the inverter devices imported into the RA are a hybrid type with the capability for storage connection, which is a very low level (Annex L).

Based on data provided by ENA, SRIE assessed the geographic locations of ASPPs connected to the grid, grouped by ENA branch 6(10)/0.4 kV substations across all 52 ENA branches. As of 2025, 39,720 ASPPs with a total installed capacity of 542.3 MW were connected to the low-voltage distribution networks of approximately 7,900 6(10)/0.4 kV substations. The data also include ASPPs with capacities up to 500 kW, consistent with the regulatory definition in force until 2022.

Derived from the analysis conducted, SRIE developed a set of policy, regulatory, and technical recommendations. Legislative and institutional recommendations include: (1) Creation of awareness mechanisms, aimed at informing existing ASPP owners, prospective owners and installers, and ENA field staff about the proper use and risks of their installations, so as to reduce voltage-related problems that can affect both ASPP owners and other consumers on the same local grid; (2) Development and implementation of a legislative and secondary regulatory framework for energy storage systems- amendments to the Energy Law to formally define and regulate energy storage, development technical regulatory framework for connection to the grid accompanied by technical standards and updated PSRC Market Rules; (3) Development and implementation of enabling mechanisms for the installation of energy storage systems, aimed at helping ASPP owners overcome the high cost of adding storage to their installations through measures such as subsidies or tax incentives; (4) Multi-tariff policy, which is the introduction of at least a three-tier electricity tariff structure to shift consumption toward peak solar generation hours (12:00-15:00), reducing surplus, curtailments, and pressure on baseload plants; (5) Market liberalization- expansion of the liberalized electricity market to include ASPP owners and low-voltage consumers, enabling self-consumption, electricity exchange, and storage-linked market participation, (6) Developments of electrical safety regulations and operation standards for SPPs- development of normative technical documents, safety regulations, and operating guidelines for SPPs covering personnel qualifications, earthing, DC isolation, and periodic inspection requirements; (7) Development of control mechanisms for ASPP connection and operation, aimed not at restricting the installation of new ASPPs but at verifying that their technical parameters are and remain compliant, so that their operation does not harm the grid or other network users; (8) Mandatory licensing and qualified personnel requirements- mandatory licensing of SPP design and installation companies regardless of grid type and voltage level, capacity, or ownership form, to ensure qualified engineering personnel perform design, equipment selection, installation, and grid connection, under the supervision of qualified organizations in this field. Technical recommendations include: (1) Activating the appropriate capabilities of the inverter devices, aimed at using the voltage control functions already present in most imported inverters to keep voltage within permissible limits; (2) ASPPs voltage control monitoring system- a continuous monitoring framework requiring ENA to systematically collect, analyze, and report smart-meter voltage

data at ASPP connection points, with threshold-based alerting and regulatory reporting obligations to PSRC; the intent is not to control the normal operation of individual ASPPs, but to detect and flag cases where voltage deviations risk harming the grid or other connected consumers; and (3) Integration of battery storage systems in distribution network, given that only 1.59% of imported inverters support battery connection, the recommended primary pathway is development of centralized battery storage systems connected to low-voltage networks, supplemented over time by DC retrofit modules for existing inverters and mandatory storage-ready requirements for all new connections. These recommendations are addressed to MTAI, PSRC, ENA, and other relevant sector stakeholders.

1. Introduction

Large-scale integration of variable renewable energy sources, particularly solar power plants, into Armenian transmission and distribution networks commenced in 2018 and has continued to expand to the present day. Although this contributes to strengthening Armenia's energy independence, it has simultaneously introduced significant technical, operational, and regulatory challenges to the power system. This issue is most critical in 0.38/0.22 kV low voltage distribution networks, where voltage values exceed permissible limits, frequently reaching 270 to 280 V. At the commencement of this assignment, approximately 35,000 ASPPs were connected to the low voltage distribution network, with a total installed capacity of about 460 MW. At present, this number has increased to approximately 50,060 units, with the total installed capacity reaching about 640 MW. However, voltage regulation issues persist to the present day, and the severity of this issue continues to increase. On the other hand, according to GOST 32144-2013, *Power Quality Standards in General-Purpose Power Supply Systems*, which is mandatory in Armenia, the long-term permissible voltage range at the consumer connection point is 198 V to 242 V. These voltage deviations not only compromise grid stability but also pose a risk of damage to consumer electrical equipment. To provide the evidence base needed to address these challenges, SRIE conducted a comprehensive technical assessment of the collected data on existing ASPPs, with a primary focus on voltage and reactive power management, compliance with operating voltage ranges, and the feasibility of integrating battery energy storage systems.

Within the scope of this assignment, SRIE has collected, validated, and analyzed technical data on ASPPs already connected to Armenia's 0.38/0.22 kV low voltage distribution networks, as well as data obtained from the RA Customs Service regarding imported inverter device marks and manufacturers for the period 2018 to July 2025.

SRIE focused on collecting and classifying key information related to ASPPs, with particular emphasis on inverter devices:

- Voltage and reactive power control capabilities,
- Capability to adjust operating voltage ranges,
- Connectivity and specifications of storage batteries,
- Installation dates and grid connection timelines.

SRIE validated the collected data through field visits. During these visits, SRIE conducted:

- Compared data provided by ASPPs installers with actual on-site validations,
- Find discrepancies between reported and actual data,
- Assessed the electrical safety issues of the installed ASPPs.

SRIE processed and organized the data received from ENA and ASPP installers into structured, digitized data sheets, which were further classified according to multiple indicators, including geographic location, technical specifications, and operational parameters, using a digital spreadsheet developed by SRIE. The data received from the RA Customs Service were also digitized into data sheets and further classified according to multiple indicators, including technical specifications and operational parameters.

The collected and digitized data on inverter devices were grouped according to technical capabilities, operational parameters, brands, and manufacturers.

2. Methodological Approach

With the support of MTAI, ENA, and ASPP installers, SRIE collected technical information on ASPPs connected to low-voltage distribution networks, including voltage and reactive power control capabilities, the ability to adjust operating voltage ranges, storage battery connectivity and specifications, and assessments of the electrical safety level of the installed ASPPs.

To enhance the scope of this research by incorporating as much information as possible on inverter devices, SRIE decided to request data from the RA Customs Service on inverter devices imported into the RA from 2018 to July 2025. Based on this information, voltage and reactive power control capabilities, as well as storage system connectivity options, were also investigated.

The Table-1 summarizes the information collected and processed as part of this assignment, indicating the organizations and stakeholders responsible for each item.

Table-1: Scope of Work and Responsibilities of the Primary Data Provider, Contractor, and Other Stakeholders

Primary data provider: ENA, ASPPs Installers, MTAI and CS	Contractor: SRIE	Other stakeholders: MTAI, PSRC, WG
Data collection: ✓ Region ✓ City, Village ✓ Date of connection of the ASPPs to the distribution network (month/year) ✓ ASPPs installed capacity, kW ✓ ASPPs model and manufacturer of the inverter device ✓ Inverter type is Hybrid (Yes/No) ✓ ASPPs performance (single phase or three phase) ✓ ASPPs solar panels model - Possibility of installing an electric storage battery (Yes/No) ✓ Installed electric storage battery capacity in A*Hour or kWh	✓ Data Validation and Cross-Checking, ✓ Data Digitization, Classification, Mapping, and Preliminary Analytics, ✓ Final Data Sheets, ✓ Recommendations for Technical, Policy and Regulatory enhancements and amendments.	Policy and regulatory recommendations and amendments

The involvement of the above-mentioned organizations enabled the prompt collection of technical information, including an inventory of inverter parameters. The data were analyzed to assess ASPP capabilities such as voltage and reactive power management, operating voltage range adjustment, and potential for battery energy storage. Information was gathered for all ASPPs connected to the networks from network operators or installers, and randomly validated through on-site visits. Inverter devices were then categorized by technical and operational parameters to identify management issues and provide targeted recommendations for improvement.

The outcomes of this assignment to be delivered by SRIE included the following:

- All collected, validated, and classified data related to ASPPs and inverter devices, digitized in Excel format,
- Technical recommendations for optimizing the integration of ASPPs into Armenia's distribution networks,

- Policy and regulatory insights to support MTAI and PSRC in the development of policy and regulatory frameworks, focusing on the integration of ASPPs into the grid without compromising system stability.

2.1 Defining the necessary sample size of ASPPs

When studying a large number of operating objects, such as in our case, it is important to develop and apply a methodology for determining the required sample size, ensuring sufficient accuracy of results that can be generalized to objects not included in the study. This methodology is essential because, at the commencement of this assignment, more than 35,000 ASPPs with a total installed capacity of over 460 MW were connected to the network. By the end of 2025, the number of ASPPs connected to the distribution networks had reached 50,060, with a total installed capacity exceeding 640 MW, and this figure continues to increase daily.

To determine the required number of ASPPs needed for the study, SRIE developed a methodology for sampling the appropriate number from the 35,000 connected to the network. The results of the study were used to develop technical solutions and recommendations. The methodology, including both the theoretical framework and the process for calculating the minimum required sample size, is presented in Annex A.

The sample size was calculated using Cochran's formula, which makes it possible to determine the required sample size based on the desired accuracy and confidence level.

$$n = \frac{Z^2 * p * (1-p)}{E^2}$$

- n - is sample size,
- Z - is the Z-score corresponding to the desired confidence level (see Table-2),
- p – is the expected proportion of one of two outcomes (note: *when there is no prior estimate for the proportion (p), it is common practice to use $p=0.5$*),
- E – is the acceptable error.

Table-2: Confidence level of sample size			
Confidence level, %	90	95	99
Z-score	1.645	1.96	2.576

$$n_{adj} = \frac{n*N}{N+n-1}$$

where:

- n_{adj} – is the adjusted sample size,
- N – is the general population volume.

The study shows that, to ensure an accuracy of 4% with a 95% confidence level for a total of 35,000 ASPPs connected to the distribution network, a sample of size $n_{adj} = 590$ is required, which is considered acceptable for this assignment (Annex A).

This indicates that the collection, validation, and analysis of technical parameters for approximately 600 ASPPs will be sufficient to capture the key technical data necessary to complete the tasks within the scope of this assignment.

Even for the most precise study, with 1% accuracy and 99% confidence for 50,600 ASPPs connected to the distribution networks, the required sample of size $n_{adj} = 12,493$.

2.2 Approach to Analysis

SRIE collected and consolidated detailed technical data on ASPP inverter devices connected to the 0.38/0.22 kV distribution network using information provided by MTAI, ENA, ASPP installers, and other stakeholders. The data were organized by regional localization and technical specifications in Excel format to support both current analysis and future studies.

The information collected from ASPPs installers was validated through on-site visits using a cross-checking methodology. Based on the validated dataset, SRIE conducted an assessment of the technical capabilities of ASPPs and digitized inverter parameters and geographic location data.

SRIE also requested information from the RA Customs Service on inverter devices imported into the RA, including manufacturers and brands, for the period 2018–July 2025, to further improve the accuracy and completeness of the research dataset by incorporating a larger number of inverter devices and their technical parameters into the analysis.

SRIE developed technical recommendations related to voltage quality improvement and storage battery integration, along with policy and regulatory insights for MTAI, PSRC, and other relevant government institutions and stakeholders.

3. Engagement and Communication of Stakeholders

The infrastructures of MTAI, ENA, ASPPs installers, the WG, and the RA Customs Service were closely involved in data collection. The main information was provided by ASPPs installers and ENA directly to SRIE using the relevant digital spreadsheet (Annex B). MTAI and PSRC are responsible for providing recommendations on policy and regulatory amendments based on SRIE outcomes. Communication among all involved organizations—namely MTAI, ENA, the WG, and ASPPs installers—was organized mainly through SRIE.

4. Data Collection, Validation and Cross-Checking

4.1 Data Collection

As part of its activities, SRIE conducted awareness-raising initiatives among relevant stakeholders to collect data on inverter devices used in ASPPs. Close cooperation was established with ASPPs installers, ENA, and MTAI, with particular emphasis on installers, to highlight the importance of providing inverter-related information.

Five major ASPP installers, whose names are not disclosed due to confidentiality, provided most of the available information. Some of them did not submit data in SRIE's prescribed format due to confidentiality concerns, the information received was sufficient for the study, as it included inverter manufacturers, models, and total installation numbers.

Despite the sufficient quantity of collected data on inverter devices, SRIE also requested information from the RA Customs Service on ASPP inverters imported into RA during the period 2018–July 2025. This decision was made to improve the accuracy of the study by including a larger number of inverter devices, as many ASPP installers did not provide information due to confidentiality.

All information collected from ASPP installers, and the RA Customs Service was studied, digitized, and assessed. Some of the data from ASPP installers were further validated through on-site visits and cross-checking.

Assessment of the collected data showed that the majority of information provided by ASPP installers met SRIE's requirements for conducting the necessary studies. Some records included only manufacturer and brand details of inverter devices, which was

sufficient for the research purposes. In total, ASPP installers provided data on 10,792 units, which, according to the methodology, is more than sufficient to achieve the required accuracy.

Assessment of data provided by the RA Customs Service showed that over 46,000 inverter devices were imported into the RA during 2018–July 2025, of which about 44,000 were included in the study, as some RA Customs Service records lacked the necessary information on manufacturers and brands.

4.2 Data Validation and Cross-Checking

SRIE validated the collected data by conducting field visits to a selection of representative ASPPs. In accordance with the adopted methodology, information verification and validation activities were carried out at randomly selected sites.

During the field visits, the SRIE compared the data provided by ASPPs with the actual on-site conditions. The checks were conducted to ensure that the official information submitted by ASPPs installers corresponds to the data observed at the facilities.

During the inspections, the SRIE not only verified the compliance of technical parameters provided by ASPPs installers but also assessed the level of electrical safety of the ASPPs' equipment.

This is because all electrical equipment in ASPPs is located within the consumer's direct contact zone. This includes the solar panels, inverter devices, DC and AC connection wiring, as well as other power-related electrical equipment.

As a result, improper installation may pose a risk to human life. Therefore, alongside verifying the technical parameters, an assessment of the electrical safety of the installed equipment in ASPPs was also conducted.

As part of this work, images of ASPPs—primarily of the inverter devices—were collected and stored. The SRIE provided this package of images without disclosing any personal information of the ASPP owners, such as installation addresses, full names, or mobile numbers (Annex J).

A total of 73 ASPPs were inspected for technical parameters, and electrical safety assessments of the associated equipment were conducted.

The inspection work was carried out in ten regions of Armenia: Yerevan, Armavir, Ararat, Aragatsotn, Kotayk, Gegharkunik, Tavush, Lori, Shirak, Syunik, in 52 settlements. The list of validated ASPPs is presented in Annex I.

As noted, during the inspections, photographs were taken of the inverter equipment and, in some cases, other electrical components of the solar plants, such as electrical panels, load switches, and circuit breakers. These images have been stored and provided to the WB team (Annex J).

The results of the revision activities showed that the information provided by the ASPPs installers largely coincided with the data verified on-site.

Only one discrepancy was reported, where the inverter provided by the ASPPs Installer did not match the type of inverter observed at the inspected ASPP.

According to ASPPs installer-provided information, there must be two inverters: SMA Sunny Tripower CORE2 and Huawei SUN2000-40KTL-M3, but during the inspection, it was found that the SMA Sunny Tripower CORE2 had been replaced by another manufacturer, Sangrow.

This isolated case may reflect a systematic issue, as noted in the methodology for the revision process described in the inception report. Currently, there is no legal regulation in the RA that would require ASPPs installers to ensure that installed ASPP equipment fully complies with standards or to provide information about any modifications made at the SPP site by the owners.

However, the checks showed that the digitally provided information largely coincided with the data collected and verified on-site, with no significant deviations or inconsistencies.

It should be noted that, according to the presented methodology, even the identification and registration of a large number of inconsistencies does not imply that the provided information from ASPPs installers is unreliable or unusable. As noted in the methodology, an actual inconsistency—such as a physical replacement of an inverter with a different type - does not hinder the research process, since the equipment has been imported into the RA and its technical parameters remain subject to analysis.

4.3 Summary of Findings

- ✓ The data provided by ASPP installers has high accuracy and mainly corresponds to the data of the actual installed ASPPs.
- ✓ There was only one case of non-compliance. The inverter device was replaced with an inverter of another manufacturer without data update in the database of the ASPPs installer.
- ✓ Even in the case of inaccuracy of provided data, the accuracy and value of research does not reduce, as the non-accuracy can be mainly due to the inverter device model inconsistency, device replacement with a device of another manufacturer or changes in device capacity, which cannot reduce the quality and accuracy of the researches, as the actual revealed inverter device was also imported to the RA and therefore the technical specification of the last are also subject to analysis.
- ✓ During the on-site validation, the installation of ASPPs electrical equipment was also evaluated from an electrical safety perspective, as the ASPPs are in immediate contact with the residents and pose a risk to their life. The observations show that, despite a high level of installation, enabling legislative mechanisms are still necessary to ensure the technical supervision over ASPPs.
- ✓ The information about the inspected ASPPs grid, region, settlement, inverter capacity, type and other technical data, compliance is presented in the Annex I.

The three analytical streams of this study; installer-provided ASPP records (10,792 units), Customs Service import data (44,137 devices), and field validation of 73 ASPPs each contributed to the final findings in distinct ways. The ENA provided geographic and capacity distribution information, which enabled regional clustering (Annex M). The Customs Service data expanded the analytical coverage of imported inverters for the period 2018–July 2025 and enabled an assessment of their voltage-control capabilities (Annexes H and K). Field inspections validated the installer data quality and provided primary evidence of electrical safety gaps. The convergence of all three streams on the ~95% voltage control capability finding gives this result a high degree of reliability and directly underpins Technical Recommendation 1 (Section 8.2.1). Conversely, the near-zero storage penetration finding (1.59%), consistent across both installer and Customs Service data, confirms the need for institutional interventions and informs Recommendations 8.1.2, 8.1.3, and 8.2.3.

5. Voltage and reactive power control

Voltage stabilization in distribution networks with connected ASPPs can be achieved using conventional distribution equipment, such as transformer tap changers, switchable capacitors connected to the substation bus, or other equipment providing voltage and reactive power regulation. However, these solutions are usually expensive and often inefficient.

A more effective approach is to utilize the capabilities of ASPPs inverter devices, specifically their voltage and reactive power control functions. All modern inverters considered in this study and released after 2018 have voltage regulation and control functions.

One of the main objectives of this study is to identify the voltage and reactive power control capabilities of ASPPs inverters connected to the distribution network or imported into the RA.

Solar inverters indicate two types of voltage control: dynamic and static.

Dynamic voltage control enables voltage regulation over a wide range by using a broad spectrum of regulation tools and control curves.

Static voltage control is typically used in older inverter models, mainly those manufactured before 2018, as well as in very low-cost variants. This technology enables voltage control primarily through power factor regulation, typically within a range of $\cos\varphi = \pm 0.8$.

The full description and theoretical background are presented in Annex C.

6. Main Standards Supporting Dynamic Voltage Control

It should be noted that to enable dynamic voltage control, inverters must be designed and implemented in accordance with standards that support this functionality. A review of relevant standards conducted by SRIE indicates that there are at least three key standards enabling dynamic voltage control, which are supported by the most modern inverters from various manufacturers (see Table-3).

One such standard is VDE-AR-N 4105 (commonly referred to as VDE-4105). This German/European standard specifies requirements for low-voltage grid-connected

generation, such as PV inverters, including grid connection, islanding prevention, voltage and frequency ride-through, reactive power management, and dynamic response behavior.

Table-3: Comparison of EN 50549, VDE-AR-N 4105, and G99/G98 Standards

Function	EN 50549 (EU)	VDE-AR-N 4105 (Germany, LV)	G99/G98 (UK)
Dynamic Voltage Control (DVC / Q(U) curve)	Required – inverters must provide voltage-dependent reactive power control (Volt-Var).	Required – one of the first standards to demand Q(U) control at LV.	Required – must provide reactive power control (power factor, Q(U), or voltage regulation mode).
P(f) Curve (Frequency–Active Power Control)	Required – inverters must reduce active power when frequency rises (frequency droop).	Required – must implement active power reduction vs frequency to protect grid stability.	Required – inverters must reduce/increase output based on frequency (UK-specific droop requirements).
LVRT / Fault Ride-Through	Required – must remain connected during short dips, support grid recovery.	Required – LVRT rules (inverters must not disconnect immediately, must ride through short faults).	Required – strict ride-through requirements (voltage and frequency disturbance survival).
Scope	EU-wide, LV & MV (harmonized).	Germany only, LV up to 1 kV.	UK only, >16 A per phase (distribution).

Summary:

- All three require DVC (Q(U)), P(f) curve and LVRT.
- VDE-4105 was the pioneer for LV rules then generalized into EN 50549.
- G99 /G98 is the UK's version, aligned but with local certification/testing requirements.
- There are many national standards that support dynamic voltage control, but they are not included in this table. For example, C10/C11 (Belgium), CEI 0-21 (Italy), IEEE 1547-2018 (USA), etc., similar to VDE-4105 and supports dynamic voltage control.

7. Data Digitization, Classification, Mapping, and Analytics

7.1 Collection and Analysis of Data provided by ASPPs Installers

From the information provided by ASPP installers, SRIE collected data on 10,792 grid-connected ASPP inverters, including 3,972 records with detailed information in accordance with SRIE format (Annex D) and 6,820 records in a simplified format (Annexes E, F).

The collected data cover all eleven regions of Armenia: Yerevan, Armavir, Ararat, Aragatsotn, Kotayk, Gegharkunik, Tavush, Lori, Vayots Dzor, Shirak, and Syunik.

Since information about the ASPPs owners, such as names, contact details and addresses of locations, is confidential, this information was not requested by SRIE. Therefore, geographic locations of the ASPPs were done by regions (Annex D).

Based on the collected information, SRIE compiled a list of more than 140 inverter models grouped by their capacities and manufacturers (Annex G), and conducted a comprehensive study of the inverters' possibilities of voltage and reactive power control, capability to adjust operating voltage ranges, connectivity and specifications of storage batteries.

The analysis of the technical capabilities of ASPP inverter devices was carried out by manufacturer and model, based on the information presented in Annex D and grouped by manufacturers—SINENG, SUNGROW, SOLAREEDGE, FOX-ESS, FRONIUS, GOODWE, HUAWEI, KACO, KSTAR, SAMIL, SMA, SOFAR, SOLAX, and SOLIS. The results are presented in Annex H.

It is mandatory in most modern grid codes (Europe: ENTSO-E, Germany: EN 50549, VDE-AR-N 4105, UK G99, Australia AS4777, etc.).

The results of a comprehensive study of inverters voltage control and hybrid technology support possibilities grouped by manufacturers are shown in the Table-4.

n/n	Manufacturer	Example Models	Hybrid Models	Voltage Control
1	Solis	S5-GR1P5K Hybrid, S6-EH1P5K-L-Pro	EH/Hybrid series	Dynamic
2	Sofar	HYD 3000-6000-ES, ME 3000SP	HYD, ME series	Dynamic
3	Solax	X-Hybrid, T-BAT, A1, X1-Boost, X3-Hybrid	X-Hybrid, T-BAT, A1, X3-Hybrid	Dynamic
4	SMA	Sunny Boy, Sunny Tripower, Sunny Island	Sunny Boy Storage, Sunny Island	Static & Dynamic (by series)
5	Huawei	SUN2000-(L1, M0, M1, M2, LC0	M1, M2, L1 residential	Dynamic

		series)	hybrid series	
6	Sungrow	SG series (RT, RS, CX, CX-P2, SH hybrid)	SH hybrid, RT hybrid lines	Dynamic
7	GoodWe	ET, ES, EM, BT, HT series	ET, ES, EM, BT	Dynamic
8	Fronius	Primo, Symo, GEN24, Tauro	GEN24 Plus Hybrid	Dynamic
9	FoxESS	H1, H3, H3-Pro, EP11, KH, R, T, G3	H1, H3, H3-Pro, EP11, KH	Dynamic
10	SolarEdge	SE (H series hybrids, three-phase SE models)	SE-Hybrid, StorEdge	Dynamic
11	KSTAR	KS, KSG, KTL series	some K series hybrids	Static & Dynamic (by model)
12	Samil	SolarRiver, SolarLake, SolarOcean	SolarRiver Hybrid	Static & Dynamic (by series)
13	KACO	Blueplanet TL, PLENTICORE	PLENTICORE hybrid	Static & Dynamic (likely support)
14	SINENG	1P10K, 3P10K, SP series	Limited (some hybrid-ready SP series)	Dynamic

Summary of Findings

- ✓ Studies show that almost all manufacturers producing inverters after 2018 support dynamic voltage control through compliance with the EN 50549, VDE-AR-N 4105, or G99 standards,
- ✓ The majority of ASPP inverter manufacturers, particularly for models produced after 2018, comply with the EN 50549, VDE-AR-N 4105, or G99 standards,
- ✓ The majority of ASPP inverters support dynamic voltage control, meaning they can regulate voltage over a wide range using curves such as $Q(U)$, $P(U)$, and $\cos\phi(P)$, etc,
- ✓ Some inverters that do not support dynamic voltage control are equipped with static voltage control, allowing $\cos\phi$ to be set to a specific value and maintaining the voltage within an acceptable range at the PCC,
- ✓ The results of the studies and initial assessments, based on information collected from ASPPs installers, show that most grid-connected inverters have dynamic voltage control capabilities, particularly models produced after 2018.
- ✓ Models that do not feature dynamic voltage control have static voltage control capabilities, allowing $\cos\phi$ to be set within the range $[-0.8, +0.8]$, and in the worst case, the $\cos\phi$ can be set to 1,

- ✓ Models that support only static voltage control represent a small portion of the total number of grid-connected inverters,
- ✓ All inverter models have the ability to set upper and lower operating voltage limits, exceeding which results in disconnection from the network,
- ✓ Most modern inverters feature a P(f) function, which allows gradual regulation of the active power output based on changes in grid frequency.

7.2 Collection and Analysis of Data provided by the Customs Service

According to the methodology, the information collected by SRIE on 10,792 grid-connected inverter devices is sufficient to ensure the accuracy of the results. Based on the methodology, analyzing the parameters of just 600 inverter devices would still be adequate to achieve the required level of accuracy.

However, considering that not all ASPP installers agreed to provide information, citing corporate confidentiality and business interests, and that inverter devices from various manufacturers were imported into the RA in large quantities, SRIE decided to request information from the RA Customs Service on the models and quantities of inverter devices imported into the RA for the period 2018–July 2025 to improve the accuracy of the research results.

In total, the RA Customs Service provided information on 46,070 inverter devices for the period mentioned above. However, information on the manufacturer and model was available for only 44,137 of these devices.

SRIE carried out a comprehensive analysis of the received information, grouped by inverter device manufacturers and quantities. The total number of the most imported inverter devices to the RA is 43,120 representing 97.71%, as shown in Table 5.

Table-5: Most imported manufacturers and quantities			
n/n	Manufacturer	Quantities	%
1	SOLAX	9,867	22.36%
2	FOXESS	5,581	12.64%
3	SOFAR	4,336	9.82%
4	HOYMILES	4,175	9.46%

5	DEYESUN	3,759	8.52%
6	SOLIS	3,610	8.18%
7	GROWATT	3,380	7.66%
8	GOODWE	2,645	5.99%
9	HUAWEI	1,968	4.46%
10	SUNGROW	1,146	2.60%
11	SOLPLANET	704	1.60%
12	RENAC	555	1.26%
13	SUNWAYS	475	1.08%
14	WELION	334	0.76%
15	MUST	258	0.58%
16	SMA	222	0.50%
17	BLUESUN	105	0.24%

The presented data indicate that there are 17 major manufacturers of inverter devices imported into the RA, with 10 of them being dominant.

The technical parameters of more than 400 inverter models from over 17 manufacturers were thoroughly analyzed and grouped by manufacturers, brands, and capacities. The results are presented in Annex K.

We conducted an analysis of the technical capabilities of inverter equipment models from the aforementioned manufacturers, focusing on voltage control and storage connection options.

Analysis of the technical parameters of inverter devices indicates that devices from the specified manufacturers generally include a voltage control option, either dynamic or static. Most manufacturers explicitly specify dynamic voltage control capabilities in their equipment datasheets. However, some manufacturers do not mention this directly but reference grid codes and standards that require dynamic voltage control, which confirms the capability of their devices.

Older inverter devices, mostly manufactured before 2018, generally lack dynamic voltage control but offer static voltage control, which achieves voltage regulation to some extent through power factor management.

Specifically, the analysis shows that inverter equipment from SOLAX, FOXESS, SOFAR, HOYMILES, DEYESUN, SOLIS, GROWATT, GOODWE, HUAWEI, SUNGROW, SOLPLANET, SUNWAYS, and SMA (depending on the model) possess dynamic voltage control capabilities. For RENAC inverters, dynamic voltage control is not explicitly indicated in the datasheets. However, compliance with G98, EN 50549, C10/11, and CEI 0-21 standards confirms this capability.

The dynamic voltage control capability is not explicitly indicated for inverters from MUST, but compliance with the VDE 4105 standard ensures this functionality. For BLUESUN and WELION inverters, dynamic voltage control is also not explicitly mentioned; however, their datasheets specify power factor control capability within the range [-0.8, +0.8].

The full list of top manufacturers imported into the RA during the above-mentioned period, along with the manufacturers' names and quantities, is presented in the Table-6.

Table-6: Top Imported Manufacturers of Inverter Devices with Voltage Control Capabilities in the RA for the period 2018-July 2025				
n/n	Manufacturer	Quantities	%	Voltage Control
1	SOLAX	9,867	22.36%	Dynamic
2	FOXESS	5,581	12.64%	Dynamic
3	SOFAR	4,336	9.82%	Dynamic
4	HOYMILES	4,175	9.46%	Dynamic
5	DEYESUN	3,759	8.52%	Dynamic
6	SOLIS	3,610	8.18%	Dynamic
7	GROWATT	3,380	7.66%	Dynamic
8	GOODWE	2,645	5.99%	Dynamic
9	HUAWEI	1,968	4.46%	Dynamic
10	SUNGROW	1,146	2.60%	Dynamic
11	SOLPLANET	704	1.60%	Dynamic
12	RENAC	555	1.26%	Presumably (G98, EN 50549, C10/11, CEI 0-21)
13	SUNWAYS	475	1.08%	Dynamic

14	WELION	334	0.76%	Indefinitely
15	MUST	258	0.58%	Presumably (VDE 4105), partly (depend on model)
16	SMA	222	0.50%	Static & Dynamic (depend on model)
17	BLUESUN	105	0.24%	Indefinitely

Manufacturers of inverter devices with dynamic voltage control capabilities are presented in Table-7. Their total number is 41,652 units, representing 94.37%.

Table-7: Manufacturers of Inverter Devices with Dynamic Voltage Control Capabilities			
n/n	Manufacturer	Voltage Control	%
1	SOLAX	Dynamic	22.36%
2	FOXESS	Dynamic	12.64%
3	SOFAR	Dynamic	9.82%
4	HOYMILES	Dynamic	9.46%
5	DEYESUN	Dynamic	8.52%
6	SOLIS	Dynamic	8.18%
7	GROWATT	Dynamic	7.66%
8	GOODWE	Dynamic	5.99%
9	HUAWEI	Dynamic	4.46%
10	SUNGROW	Dynamic	2.60%
11	SOLPLANET	Dynamic	1.60%
12	SUNWAYS	Dynamic	1.08%

Some manufacturers do not explicitly specify the dynamic voltage regulation capabilities of their inverter devices, and certain manufacturers or models may not support this functionality at all. SRIE studies showed that their total quantity is approximately 1,440 units, representing 3.34% of the total. Of these, about 1% are inverter devices with undefined dynamic voltage regulation capabilities, while 2.34% are presumed to have such capabilities, although not explicitly specified. Information on these manufacturers is presented in Table-10.

Table-8: Manufacturers of Inverter Devices Without Explicit Dynamic Voltage Control Capability			
n/n	Manufacturer	Voltage Control	%
1	RENAC	Presumably (G98, EN 50549, C10/11, CEI 0-21)	1.26%
2	WELION	Indefinitely	0.76%
3	MUST	Presumably (VDE 4105), partly (depends on the model)	0.58%
4	SMA	Static & Dynamic (depend on model)	0.50%
5	BLUESUN	Indefinitely	0.24%

Taking into account the above-mentioned Tables it can be assumed that 94.37 % of the inverter devices imported in the RA have the capability for the dynamic voltage control.

Research was also carried out on the ability of connecting storage batteries to the inverter equipment. As a result, it was clear that nearly 1.59 % of the inverter devices imported into the RA are a hybrid type with the capability for storage connection which is a very low level (Annex L).

Summary of Findings

- ✓ During the above-mentioned period over 46,000 inverter devices from various manufacturers were imported to RA for period 2018-July 2025.
- ✓ The list of models and manufacturers of ASPPs inverters, most imported in the RA in the specified period, is given in Annex 3.B.
- ✓ The SRIE has made an overall analysis of the received information - grouping by inverter devices manufacturers and quantities. As a result, data on 43,120 inverter devices imported in the largest volumes was processed according to manufacturers and importing volumes.
- ✓ Around 94.37 % of the observed inverter devices have the capability of dynamic voltage control. Some producers state that obviously, some do not, but they are compliant with standards that require dynamic voltage control, especially for inverters manufactured after 2018.
- ✓ Only 1.59 % of the observed inverter equipment has the capability for storage connection.

7.3 Geographic location and Mapping

Based on information provided by ENA, SRIE processed data and conducted studies on the geographic location of ASPPs connected to the grid, grouped by 6(10)/0.4 kV substations of ENA branches.

The total number of substations for 52 networks of ENA, to the low-voltage network of which the ASPPs are connected, was considered. Their total number and capacity were calculated by networks. As a result, it turned out that as of 2025 totally 39,720 ASPPs with an installed capacity of 542,257 kW have been connected to the low-voltage networks of 7,900 substation of 6(10)/0.4 kV in 52 networks.

It should be noted that it also included up to 500 kW ASPPs, since until 2022 the capacity of ASPPs was allowed up to 500 kW inclusive.

The geographic location of individual ASPPs was not provided due to owner confidentiality, making it impossible to map.

Summary of Findings

- A grouping of the ASPPs was carried out by geographic location. As a result, it turned out that totally 39,720 ASPPs with an installed capacity of 542,257 kW have been connected to the low-voltage distribution grid of 7900 substation of 6(10)/0.4 kV in 52 branches of “ENA” CJSC (Annex M).
- The geographic location of each ASPP was not provided due to owner confidentiality, making it impossible to map.

8. Policy and Regulatory Insights and Technical Recommendations

8.1 Legislative and Institutional Recommendations

1. **Creation of awareness mechanisms.** It is very important to create the awareness mechanisms for the ASPPs owners, regardless of the form of ownership that will increase the level of awareness of ASPPs owners. These mechanisms will increase awareness among ASPP owners, highlighting the positive and negative aspects as well as recent developments in this field, with the participation of the Government and other stakeholders. One significant negative impact to consider is the challenges that arise within the network, related to voltage operating regimes. These problems adversely affect not only other electricity consumers supplied from the same feeder but also the owners of the ASPPs, whose grid-connected electrical equipment is primarily impacted, potentially leading to equipment malfunction or even damage. The highlight of positive aspects should be implemented by providing information and raising awareness on the development of technical and financial measures addressing these issues by government agencies, infrastructures and other stakeholders. Raising awareness requires a mix of communication strategies, education tools, and practical engagement. The selection of these groups reflects the three key groups within the ASPP lifecycle where awareness gaps have the greatest impact on grid stability: existing owners, new owners and installers, and ENA field staff.

Three distinct groups for these awareness-raising measures should include: (i) ASPP owners who are unaware that their inverters have voltage control capabilities that can be activated; awareness here supports compliance with the mandatory activation decree proposed in Section 8.2.1; (ii) prospective ASPP owners and installers, who should be informed of new minimum connection requirements before connection; and (iii) local ENA engineers and inspectors, who need training on monitoring and interpreting PCC voltage data. MTAI should coordinate the development of a concise technical guidance note for ASPP owners, and PSRC should require ENA to issue connection-stage information materials as part of the standard ASPP connection procedure. Demonstration projects should only be proposed once the minimum requirements framework is adopted, and a pilot substation has been identified.

2. Development and implementation of legislative and secondary regulatory frameworks for energy storage systems. The deployment of energy storage systems across all voltage levels of the power system is a critical necessity, both for regulating voltage regimes and ensuring permissible network loading conditions, and for addressing system-level issues and maintaining power balance. At the same time, storage deployment enables the avoidance of operational challenges for baseload power plants, including reductions below their technically permissible minimum output, shortened service life, creation of additional financial obligations for the state, and the emergence of constraints on economically efficient operating modes.

It is important that energy storage systems be installed at each voltage level, accumulating energy generated at that respective voltage level. A coordinated approach to storage deployment across all voltage levels can deliver system-wide benefits for Armenia's electricity network. Targeted storage investments at transmission, medium-voltage, and low-voltage levels can support voltage regulation, reduce congestion, improve flexibility, and create solutions that serve a broad range of participants, including consumers, small businesses, large commercial users, distribution network operators, and the transmission system. Across all these levels, the primary function of storage is to keep the system in balance, absorbing surplus generation when supply exceeds demand and releasing it

when demand exceeds supply, which is what in turn supports voltage regulation, eases congestion, and creates the flexibility described above.

There is currently no regulation governing the energy storage systems sphere in the RA, neither at the legislative level nor within secondary regulations. Additionally, there is no technical documentation addressing the installation, maintenance, and operation of such systems.

Therefore, it is necessary to introduce appropriate amendments to the Energy Law, develop technical documentation for the installation, maintenance, and operation of energy storage systems, and implement corresponding changes to the Market Rules and other documentation issued by the PSRC of the RA.

SRIE has developed technical rules on “Minimum Requirements for Connecting ASPPs to Low- and Medium-Voltage Distribution Networks”, which have been submitted to the MTAI for circulation and further approval by the Government.

The aforementioned rules establish technical requirements for the inverter equipment of newly connected, reconstructed, and refurbished ASPPs. These technical requirements are intended to ensure proper voltage and reactive power control, compliance with permissible harmonic distortion limits, and the maintenance of safety standards under both normal and emergency operating conditions during parallel operation with the grid.

The necessary regulatory changes include three levels: (1) Primary legislation: The Energy Law of the RA currently does not define energy storage systems as a regulated category. An amendment is needed to introduce the definition of energy storage, its classification by voltage level and capacity, the rights and obligations of storage owners, and the framework for market participation. As of the preparation of this report, amendments to the Energy Law are understood to be under development; the present study recommends that storage system regulation be explicitly included in that process. (2) Secondary regulations: The authorized institution, in coordination with relevant sector stakeholders, should develop and adopt technical connection rules for storage systems according to their functional role in the network. These rules should address safety requirements, grid interaction parameters, metering arrangements, data exchange, and reporting obligations.

A qualified technical body may support the preparation of operational and technical documentation for the installation, maintenance, and inspection of storage systems, with subsequent submission to MTAI or another competent authority for consideration and adoption, as applicable. This regulatory mechanism should be developed through coordination among the competent state authorities and sector stakeholders, within the applicable legislative and regulatory framework.

3. Development and implementation of enabling mechanisms for the installation of energy storage systems. The number of installed ASPPs exceeds 50,000, yet the studies show that only 1.59% of inverter devices imported into the RA and connected to the grid have the technical capability to connect batteries. Therefore, the majority of imported inverter devices do not support the integration of energy storage systems. To enable these ASPPs to participate in energy storage deployment, support from the state or other relevant stakeholders is required. For example, effective mechanisms include flexible state subsidy schemes, tax relief or partial tax refund mechanisms, as well as any other measures that would support emerging development trends in the solar energy sector.

For the development and implementation of incentives for the deployment of energy storage systems, the process should be divided into two parts: (i) the installation of storage systems for already installed ASPPs, and (ii) the integration of storage systems in new ASPPs or as standalone storage installations.

The integration of energy storage systems with new ASPPs depends on the capability of inverter devices to connect to storage systems. The SRIE has developed a document titled *“Minimum Technical Requirements for Connecting ASPPs to Low- and Medium-Voltage Distribution Networks,”* which requires that inverter devices connected to the grid must have the capability to integrate with energy storage systems. This technical documentation is currently under circulation among the organizations of MTAI, after which it will be submitted to the Government for approval. As the cost of energy storage systems remains relatively high, it is necessary to introduce financial incentives and effective support mechanisms from the state or other stakeholders. These should include flexible state subsidy schemes, tax incentives or partial tax refund mechanisms, as well as enabling participation in the electricity market.

We believe that state subsidies and tax incentives be provided only for the installation of ASPPs combined with energy storage systems, or for standalone energy storage systems. At the current level of solar energy integration, it is not feasible to further increase the share of renewable energy without the deployment of energy storage solutions.

4. Multi-tariff policy. The two-tariff system, in the context of the rapid development of solar energy in the RA, does not sufficiently address issues related to electricity consumption regimes. The introduction of a multi-tariff policy, at least a three-tariff system, could more effectively encourage electricity consumption during peak solar power generation hours.

One of the main constraints affecting the further development of solar energy is the need for energy storage systems, while the economic attractiveness of such systems remains relatively limited. Therefore, to minimize the required scale of storage system deployment, it is necessary to promote electricity consumption during surplus generation hours, particularly between 12:00 and 15:00.

This issue is especially relevant in low-voltage networks, where ASPPs generate maximum electricity during periods of minimum consumption. Consequently, incentives should be created to encourage local electricity consumption within these periods. One of the most effective mechanisms for achieving this objective is the introduction of a multi-tariff policy that would encourage increased electricity consumption in the residential sector while maintaining consumer comfort, shift household consumption patterns toward economically favorable periods, and stimulate industrial and other consumers to concentrate electricity consumption during tariff-favorable hours.

At present, during periods of surplus electricity generation, instructions are already being issued by the TSO (EPSO) of the RA to disconnect certain industrial solar power plants from the network. This occurs because system-critical power plants reduce their output to technical minimum levels during such hours, and any additional reduction may negatively affect system reliability and operational stability.

The disconnection of SPPs not only results in the loss of electricity generated during maximum solar production hours but may also lead to additional financial obligations

associated with compensation for curtailed generation. Ultimately, this may contribute to increases in electricity tariffs for end consumers.

In light of the above, it is proposed to consider the introduction of a multi-tariff system with at least three differentiated tariffs aimed at optimizing electricity consumption behavior, reducing renewable energy curtailment, and improving overall system efficiency.

5. Market liberalization. Expanding the electricity market liberalization process with the inclusion of ASPPs and consumers connected to low-voltage distribution networks can support more efficient integration of solar energy and future energy storage systems. In particular, the development of mechanisms enabling the formation of different groups of solar PV producers and consumers may create additional flexibility opportunities within the distribution network.

One of the key objectives should be the creation of mechanisms that allow ASPP owners and consumers to participate more actively in electricity market processes, including self-consumption arrangements, electricity exchange mechanisms, and future storage-related activities. Such approaches could create additional incentives for improving local balancing of electricity generation and consumption within distribution networks.

The development of flexible mechanisms based on liberalized market principles and dynamic interaction among consumers connected to the same distribution network may contribute to increasing local consumption of produced electricity and reducing operational challenges associated with surplus solar generation.

At the same time, the current market framework and existing Market Rules provide limited mechanisms and incentives for broader participation of distributed renewable energy producers and future storage systems. Therefore, further assessment and gradual development of appropriate regulatory and sub-regulatory mechanisms may be required.

According to PSRC analytical report on electricity market indicators regarding the ongoing electricity market liberalization process in the RA, the liberalized market segment and participation volumes continue to expand annually, including the number of qualified consumers and market participants. In this context, future development of additional mechanisms related to distributed renewable energy resources and ASPPs may also be considered within the broader market liberalization framework.

The implementation of such mechanisms would require coordinated involvement of relevant stakeholders, including competent state authorities, ENA, market operators, and other sector participants. Necessary changes may primarily relate to sub-legislative and regulatory acts, including potential amendments to market-related regulations and technical rules.

6. Developments of electrical safety regulations and operation standards for SPPs.

There are not any normative technical documents, regulations, standards, operating guidelines, or safety requirements in the RA for SPPs that ensure their uninterrupted, safe, and reliable operation, as well as the electrical safety of both personnel and end consumers. Field inspections of SPPs have shown that, despite the generally satisfactory condition of their electrical equipment, the absence of such technical documentation remains a pressing issue—particularly with regard to safety regulations, as these directly affect the protection of life and health of both operating personnel and consumers.

This need is especially urgent in relation to electrical safety rules for SPP operation, which establish requirements for plant personnel and, in the case of low-voltage networks, ensure the safety of ordinary consumers.

The safety standards should cover at minimum: (a) earthing and lightning protection requirements; (b) qualification requirements for personnel performing installation and maintenance; (c) periodic inspection obligations for operational ASPPs; (d) mandatory labeling and isolation requirements for DC components.

The responsible body for organizing the development process is the MTAI, with possible participation from other stakeholders.

7. Development of control mechanisms for ASPP connection and operation. According to the distribution networks' rules and the retail electricity market rules, no control mechanisms are defined for the connection or further operation of the ASPPs. This creates numerous challenges both at the grid connection stage and during operation. The absence of technical regulations and proper control mechanisms allows APPs to connect to the network with virtually no restrictions on their technical characteristics or power. During operation, changes in the composition and capacity of plant equipment—such as

modifications to inverter capacity, the number of photovoltaic panels, and other components - may occur. These changes can qualitatively alter the plant's behavior at the PCC and its impact on the grid. To address these challenges, at the connection phase of ASPPs to the grid, the compliance of the electrical equipment with the declared technical parameters must be verified. The verification must be assigned to an independent specialized scientific and technical organization. Regarding the re-inspection of the electrical equipment at the SPP during operation, we think this should be the exclusive function of a state authority, such as the Urban Development, Technical, and Fire Safety Inspectorate of the RA. To implement this, it is necessary to introduce amendments to the PSRC regulations.

8. Mandatory licensing and qualified personnel requirements. At present, the RA has more than 100 companies engaged in the import and installation of SPPs. Although it is considered a critical requirement, the availability of qualified engineering and technical staff capable of designing, selecting equipment appropriately, installing, and connecting to the grid, and ensuring SPP electrical safety is not regulated.

8.2 Technical Recommendations

1. Activating the appropriate capabilities of the inverter devices. Studies indicate that approximately 95% of inverter devices imported into the RA are equipped with voltage control functionalities. By activating these capabilities, it is possible to facilitate electricity generation while maintaining voltage levels within permissible limits, or at minimum, mitigating abnormal voltage deviations.

Where inverter devices support dynamic voltage regulation, this can be achieved through control modes such as Q(U) (reactive power–voltage control), P(U) (active power–voltage control), $\cos\phi(P)$ (power factor–active power control), fixed reactive power (Q), or other equivalent strategies.

In cases where inverter devices are limited to static regulation capabilities, voltage support is typically provided through power factor control within a range of ± 0.8 , achieved via reactive power adjustment. Although such approaches do not ensure full voltage regulation,

they can contribute to partial stabilization of voltage conditions at the PCC between the ASPP and the grid.

To enable the effective utilization of these capabilities, it is necessary for the Government to adopt a decree mandating that all ASPPs equipped with inverter devices possessing voltage control functionalities activate and appropriately configure these features in accordance with the technical requirements for connecting ASPPs to the distribution network.

Based on the study findings and the technical capabilities identified in most imported inverter devices, the SRIE Team suggests considering a phased implementation approach for activating inverter voltage control functions. In the first phase, ENA, as the distribution network operator, could inform registered ASPP owners about the recommended activation of voltage control functionalities through existing metering, billing, and customer communication channels. In the second phase, ASPP owners could engage the original installer or another qualified technician to configure the relevant voltage control mode in line with the approved minimum technical requirements. In the third phase, as distribution network data collection and analytical capabilities improve, ENA could gradually introduce feeder-level voltage monitoring and analysis to identify areas where voltage deviations persist after activation of inverter voltage control functions.

The implementation of these mechanisms would depend on the scope of available data, the condition of existing metering infrastructure, and the level of distribution network digitalization. Further diagnostic work would help determine the appropriate monitoring architecture, including the balance between software-based data analysis, smart-meter data use, and any additional hardware needs.

In parallel, further investments and modernization of low-voltage distribution networks may be necessary to ensure the effective implementation of advanced voltage management and monitoring mechanisms in the future.

2. ASPPs Voltage Control Monitoring System. A system for continuous monitoring of the operating conditions of grid-connected SPPs. The monitoring system should record violations of acceptable parameters and, when necessary, initiate disconnection from the grid. To this end, it is essential to establish a system for monitoring operating parameters,

specifically the voltage at the PCC with the grid. To achieve this, an appropriate regulatory and technical framework must be established. The ENA should be responsible for the integration of the monitoring system into the distribution networks. The relevant regulations should be adopted by the PSRC and MTAI. The monitoring system proposed here does not necessarily require new metering hardware, it requires: (i) a systematic protocol for ENA to collect, store, and analyze smart meter voltage data by ASPP; (ii) threshold-based alerting when individual ASPPs consistently exceed the 242V upper limit; and (iii) a regulatory reporting obligation to PSRC on voltage deviation incidents. ENA should be required, under its distribution license conditions, to operate voltage monitoring as part of its network management obligations. The cost of this function, estimated to be primarily a software and data management cost, given existing metering hardware, should be recoverable through ENA's regulated tariff, subject to PSRC approval of the relevant investment in its next tariff review. PSRC should amend the Distribution Network Rules to impose an explicit voltage monitoring obligation on ENA, including reporting requirements and response protocols for persistent voltage violations.

3. Integration of Battery Storage Systems in Distribution Network. Studies indicate that only 1.59% (702 inverter devices) of the analyzed inverter devices have the capability to connect to a battery energy storage system. The results of the analysis, including detailed information on manufacturers, inverter models, and import volumes into the RA, are presented in Annex L.

Based on these findings, it can be concluded that the capability to integrate energy storage systems into ASPPs imported into the RA and connected to distribution networks is almost entirely absent. Therefore, it is necessary to introduce targeted incentives to modernize already connected ASPPs or to develop alternative measures to address this limitation.

Research conducted by the SRIE on practical experience indicates that only a few technical solutions exist for this issue. Based on the findings, the following options have been identified as the most effective for addressing the problem:

a) Replacement of existing inverter devices with units that support battery energy storage system integration. Replacing existing inverter devices with ones that support battery connection is one of the most effective measures. However, it is also a costly solution, as it requires replacing all current inverter devices with new ones.

In addition, as noted above, approximately 95% of inverter devices imported into the RA are equipped with voltage control functionality and can therefore be considered technically adequate; consequently, their replacement would be inefficient and economically unjustified.

b) Application of Intermediate Electrical Equipment for Battery Connection to Existing Inverters. This approach involves using new devices that allow a battery system to be connected to conventional grid-tie inverters without requiring a hybrid inverter. The device connects to the DC side of a PV string and does not interfere with the MPPT. This technology is referred to as a DC Retrofit Energy Storage Module or PV-side DC Energy Storage Optimizer. In industry terminology, it is also known as an Inline DC Storage Module, DC String-level Storage Interface, PV-DC Battery Retrofit Unit, or DC-coupled Energy Storage System for grid-tie inverter (retrofit). It is worth noting that in European countries, certified inverter devices carry registered product codes that legally prevent replacement without re-certification, making retrofit the only compliant pathway. Armenia has no equivalent certification framework, so there is no regulatory barrier to replacement. However, given the economic cost of full replacement at scale, the retrofit approach remains the more economically justified option in the Armenian context.

This solution is among the most effective for integrating storage. However, one major drawback is the high initial cost of retrofitting, which can be nearly equivalent to that of a new inverter device. It should be noted, however, that as a new technology, this cost is expected to decrease over time as the technology matures and adoption increases, making it a more attractive option in the long term.

c) Establishment of Centralized Battery Storage Systems. In the current situation, when a great part of the inverter devices imported to the RA have no ability of connecting to storage systems, it would be more advisable not to re-equip the available inverter devices with new inverter equipment or other no less expensive auxiliary devices that will ensure technical ability of connecting the inverter devices to the storage system, but develop and introduce centralized systems of energy storage devices connected to low-voltage networks. This approach will be an efficient solution to almost all of the regimes' concerns and will also avoid the costly upgrades to the electrical equipment of individual SPPs.

For the implementation of the above-mentioned institutional and technical recommendations, the participation and involvement of all relevant stakeholders, including

MTAI, ENA, PSRC, the Government of the RA, and other relevant stakeholders, is required. A more in-depth review of the recommendations is beyond the requirements of the assignment of this study.

Based on Customs Service data covering inverter imports for the period 2018-July 2025 (Annex L), only 1.59% of imported inverter devices are hybrid models with battery connectivity capability, indicating that the majority of the existing inverter fleet currently lacks integrated storage functionality.

Hence, the study considers several potential approaches for enabling broader battery storage integration within Armenia's distribution networks. These include replacement of existing inverter devices with storage-compatible units, application of DC retrofit technologies and intermediate electrical equipment enabling battery connection to existing inverter systems, as well as the possible development of centralized battery energy storage systems connected to distribution networks.

Each of these approaches has distinct technical, operational, and economic characteristics, advantages, and limitations. Their applicability may differ depending on factors such as network conditions, existing infrastructure, technical compatibility of installed equipment, operational requirements, investment needs, and long-term system development priorities. Therefore, all identified approaches should be considered within future policy, regulatory, technical, and investment planning processes related to battery storage deployment and ASPP integration.

For new ASPP connections, the "Minimum Technical Requirements" document submitted to the MTAI already provides storage-ready inverter capability requirements, thereby supporting the gradual expansion of storage-compatible installations in future network developments.

At the same time, the specific technical parameters, siting approaches, sizing methodologies, operational models, and financing mechanisms associated with broader deployment of battery storage systems have not been assessed within the scope of the present study and may require separate dedicated technical, economic, and feasibility assessments in the future, including potential use of the substation-level ASPP distribution data presented in Annex M.

An additional aspect requiring further assessment relates to the operational interaction between increasing ASPP penetration, system balancing requirements, and the

operating regimes of large-scale generation facilities operating within the power system. In this regard, future technical, economic, regulatory, and operational studies may also assess the potential role of battery storage systems in supporting system balancing, operational flexibility, and reliability under conditions of increasing renewable energy integration.

This issue is becoming increasingly important for the Armenian power system. To ensure reliable operation, Armenia needs to deploy energy storage systems capable of shifting surplus electricity—especially from solar PV—to the evening peak demand period. A critical but insufficiently examined aspect concerns the Armenian Nuclear Power Plant (ANPP), the Yerevan TPP, and other conventional power plants that form the basis of the system. These baseload facilities must operate at strict technical minimum levels during hours of high solar output. As solar generation continues to grow, this constraint places rising operational pressure on conventional units. Centralized storage would help absorb excess solar generation and release it during peak hours, improving system balance and protecting the stable operating regime of conventional plants. With this concern, a thorough investigation should be carried out to define storage system capacities, technical and economic parameters, and their placement within the power system, along with the ancillary services framework. While this is important for all conventional power plants, the ultimate importance is to be paid with regard to the nuclear power plant, taking into consideration the nuclear security and operation safety.

9. Conclusions

The results of the study based on information obtained from the RA Customs Service on inverter devices imported into the RA for the period 2018–July 2025, as well as information obtained from ASPP installers, show that about 95% of the about 44,137 inverter devices have voltage regulation capability. This means that, as a result of institutional regulations, it is possible to create preconditions under which ASPPs connected to the distribution network will carry out electricity generation primarily while ensuring permissible voltage levels at the PCC to the distribution network, or at least a significant improvement in abnormal voltage deviations will occur.

It should be noted that ASPPs connected to distribution networks and operating in parallel with the grid contribute to significant voltage rise at the PCC during peak generation periods, which—depending on seasonal conditions and solar irradiance—typically occur

between 12:00 and 15:00. In such conditions, phase-to-neutral voltage levels may reach 260–290 V, and in some cases even higher.

This is also due to the fact that the peak generation hours of ASPPs largely coincide with the minimum consumption hours of the consumers producing that energy. As a result, almost the entire volume of electricity generated by the ASPPs is transmitted to the grid. Moreover, this process occurs simultaneously across the entire system, creating operational uncontrollability in both the power system and the distribution networks, driven by challenges in ensuring voltage quality parameters and maintaining the system's energy balance. Consequently, numerous problems are already arising in meeting the technically minimum required operating regimes of base-load power plants.

The outcomes of the study, based on information obtained from the RA Customs Service for the period 2018–July 2025, indicate that only 1.59% (702 units) of inverter devices imported into the RA have the capability to connect a storage battery, demonstrating an almost complete lack of this functionality. Given this, large-scale individual-level retrofit, or replacement is not a proportionate response to the scale of the problem. This underpins the recommendation for centralized battery storage systems connected to low-voltage distribution networks as the primary pathway for the existing fleet, alongside the mandatory storage-readiness requirement for all new connections under the Minimum Technical Requirements currently under Government approval. During on-site cross-checking, validation, and inspection of ASPPs connected to the distribution network conducted by SRIE, attention was also paid to ensuring the electrical safety of the equipment in the ASPPs. Information was collected on the geographic location of the ASPPs relative to the number of ENA network branches and substations.

As a result of the research, SRIE has developed policy and regulatory insights and technical recommendations, the adoption of which by competent authorities could contribute to enabling the regulation of ASPPs connected to the distribution network and mitigate their negative impact on the voltage regimes of both transmission and distribution networks. The recommendations also aim to promote the development of storage systems by creating favorable conditions for their deployment, and to establish the necessary legislative and sub-legislative regulatory framework for the development of solar energy,

while ensuring the safe operation of electrical equipment in ASPPs and protecting human electrical safety.

Policy and regulatory insights, along with technical recommendations developed by SRIE, support MTAI, PSRC, and other relevant stakeholders in developing the necessary regulatory framework and state policies aimed at improving the quality of electricity generated by ASPPs and increasing the permissible penetration level of variable renewable energy in the RA.

In conclusion, it should be noted that, under current conditions, effective solutions can only be achieved by uniting the efforts of the government, state agencies, infrastructure and regulatory authorities, and other stakeholders, through the joint development and implementation of legislative, regulatory, and technical measures.

Annexes

The following annexes accompany this report as separate electronic files. Each annex title links directly to the corresponding document.

Annex A [Defining the necessary sample size of ASPPs](#)

Annex B [Inventory spreadsheet for collecting information regarding ASPPs connected to the distribution network](#)

Annex C [Technical Possibilities for Voltage and Reactive Power Control](#)

Annex D [List of ASPPs inverters with geographic location by cities and villages](#)

Annex E [Names of manufacturers and models of ASPPs inverters without geographic location \(about 6,000 ASPPs\)](#)

Annex F [ASPPs installed inverters by manufacturers, capacities, phase performance \(single phase or three phases\) and quantities](#)

Annex G [The name of models and manufacturers of ASPPs inverters which were collected during data collection](#)

Annex H [Comprehensive study of ASPPs inverters technical capability grouped by manufacturers](#)

Annex I [List of Validated and Cross-checked ASPPs inverters with geographic location by cities and villages](#)

Annex J [Images of ASPPs equipment validated through site visits and cross-checking](#)

Annex K [The list of models and manufacturers of ASPPs inverters, most imported in the RA for the period 2018–July 2025](#)

Annex L [ASPPs hybrid inverter manufacturers, models, and quantities imported in the RA for the period 2018–July 2025, based on information provided by RA Customs Service](#)

Annex M [Total number and capacity of the ASPPs by the networks and substations of the “ENA” CJSC](#)