Optimizing Standalone Solar Power Systems: Addressing Load Variability Impact on Battery Life in Remote Applications

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***Abstract*— When designing an optimal autonomous power supply system for residential houses or other individual objects located far from the main distribution networks, it is essential to consider the variability of the load, especially when utilizing renewable sources like photovoltaic (PV) solar panels and wind generators. Proper modeling of the stochastic nature of the load is crucial for ensuring that the demand within the microgrid is met effectively using renewable energy, supported by Battery Energy Storage Systems (BESS) and voltage regulation devices. Addressing this challenge can significantly enhance the reliability and sustainability of off-grid systems that prioritize renewable energy sources. Simulations are conducted over three consecutive days with limited sunlight during the year, and the resulting data are analyzed to assess their impact on system performance and battery life. The modeling was performed using PVSyst software version 7.3. The findings underscore the importance of considering load fluctuations in the design and operation of stand-alone residential PV systems. The paper offers insights into how these systems can be optimized to mitigate the adverse effects of load variability, thereby enhancing their overall efficiency and longevity.**

Keywords—Off-Grid PV Systems, Load Fluctuations, Variable Generation, Battery Life Span, PVSyst, residential systems

I. Introduction

The analysis and modeling of load stochasticity in distributed generation microgrids with variable renewable energy sources is crucial for mitigating the rapid fluctuations in current and voltage that these random processes cause. Such fluctuations can negatively impact the efficiency of solar panels and overall system performance.

Load fluctuations in standalone PV+BESS systems are inherently stochastic due to variations in user behavior, appliance usage, and environmental factors. These fluctuations can be modelled using probability distributions, which provide a mathematical framework to predict energy demand.

In off-grid PV systems, one of the primary drivers of load variability is the intermittent nature of solar power generation. PV systems rely on solar energy, and the available energy can vary significantly due to factors like weather conditions and time of day. Consequently, the power output of a PV system can experience rapid changes, leading to instability in system voltage and current.

Another factor that can contribute to load fluctuation is the type of load connected to the system. Certain types of loads, such as motors or pumps, can create sudden spikes in power demand when they start up or shut down, causing a rapid change in the system's voltage and current. Other types of loads, such as lighting or electronics, may have a more gradual change in power demand, but can still cause fluctuations if they are not properly sized for the system.

To mitigate load fluctuation in standalone PV systems, several strategies can be employed. One common approach is to use energy storage systems, such as batteries, to smooth out fluctuations in power output. This enables the system to capture surplus energy produced during times of strong sunlight and use it when energy demand is high. However, these batteries shall be considered in proper system design and component selection which is also crucial for minimizing load fluctuation in standalone PV systems. connected loads, and the components must be selected to ensure reliable operation under varying conditions.

A. Abbreviations and Acronyms

BESS: Battery Energy Storage System
DOD: Depth of Discharge
DiffHor: Diffuse Horizontal Irradiance
E Avail: Energy Available
E Load: Energy Load
E Miss: Energy Missing
E User: Energy Used
GlobHor: Global Horizontal Irradiance
GlobInc: Global Inclined Irradiance
LiFePO4: Lithium Iron Phosphate Battery
MPPT: Maximum Power Point Tracking
Pr LOL: Probability of Loss of Load
PV: Photovoltaic
RES: Renewable Energy Sources
SOC: State of Charge
STC: Standard Test Conditions

II. Description of Methodology

The proposed methodology focuses on estimating the power generation capacity of the solar power system under varying solar radiation conditions specific to the study area. It examines solar radiation intensity not only on December 21, the day with the lowest solar radiation of the year, but also over three consecutive days of reduced sunshine typical for the location. This article analyses two factors impacted by load fluctuation in stand-alone PV system: Performance ratio and battery state of charge (SOC).

Performance ratio and battery state of charge (SOC) are both important metrics in off-grid PV systems The performance ratio is a measure of the efficiency of a PV system and is calculated by dividing the actual energy output of the system by its expected energy output. A higher performance ratio indicates that the system is operating more efficiently and can help identify any issues or inefficiencies in the system. By monitoring the performance ratio of a stand-alone PV system, system owners and installers can identify potential problems and optimize the system for maximum efficiency.

The battery state of charge is a measure of the amount of energy stored in the battery as a percentage of its total capacity. In stand-alone PV systems, batteries are often used to store excess energy generated by the PV panels during the day, which can then be used to power the residence at night or during periods of low sunlight. Monitoring the battery SOC is important to ensure that the system has sufficient energy reserves to meet the household's energy demands. If the battery SOC falls too low, the system may not be able to meet the household's energy demands, which can result in power outages or other issues.

A. System Parameters

In our previous studies for Hovuslu village in Karabakh Region of Azerbaijan Republic [1] we have done a comprehensive analysis and calculation to identify the optimal size of stand-alone PV system with fixed load profile (Fig. 1) where total daily household energy needed is equal to 9 kWh/day.

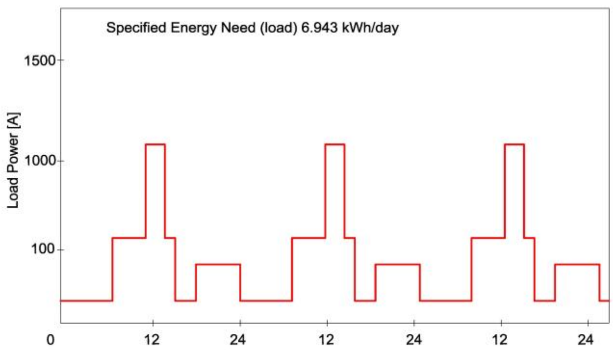


Fig. 1. Fixed Load Profile

The system component parameters are detailed in Tables 1 and 2. It features a universal charger controller and employs direct coupling. Simulation results indicate that the user's energy needs can be entirely met by solar power, achieving a solar fraction of 1.0 (Fig.2).

The system attains a performance ratio of nearly 81%, accounting for system losses. The total available solar energy for the area amounts to 3,794 kWh per year, with an actual energy usage of 3,540 kWh annually. This results in a surplus of 155.6 kWh per year, which could accommodate additional home appliances in the future. The proposed system demonstrates zero missed energy and zero load loss, indicating that the available solar energy is utilized efficiently.

According to Fig. 3, the battery's maximum depth of discharge (DOD) drops below 0.2 only for 2-3 days in February and March, while it remains above 0.5 for the majority of the time, which is beneficial for its lifecycle [7].

TABLE I. PV MODULE PARAMETERS AND RATINGS

Category	Specification
Maker	Swiss Solar
Serial Number	IBEX-72M-72
Technology	Si-mono
Number of PV panels	6
Nominal PV Power	390Wp
Fixed tilted plane	30°
Open circuit voltage (V_{oc})	48.94V
Short-circuit voltage (I_{sc})	10.240A
Modul efficiency	21.51%
Operating temperature	25 °C

TABLE II. BACK-UP BATTERY PARAMETERS

Category	Specification
Maker	Generic
Each battery Rating	180Ah
Technology	Li-ion
Total number of batteries	18
Total Capacity	3240Ah
Battery Voltage	26V

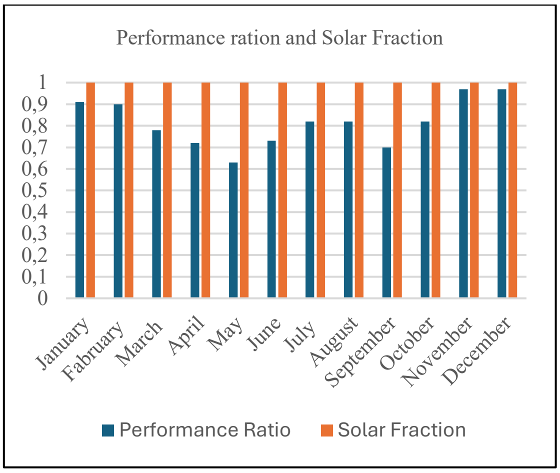


Fig. 2. Performance ratio and solar friction

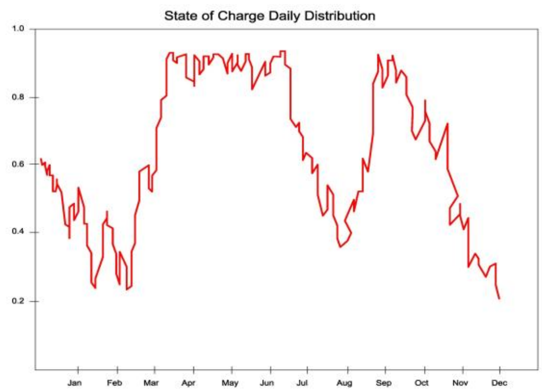


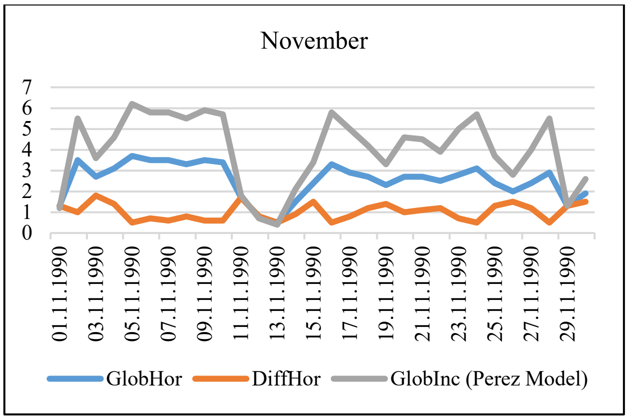
Fig. 3. Battery Average State of Charge distribution

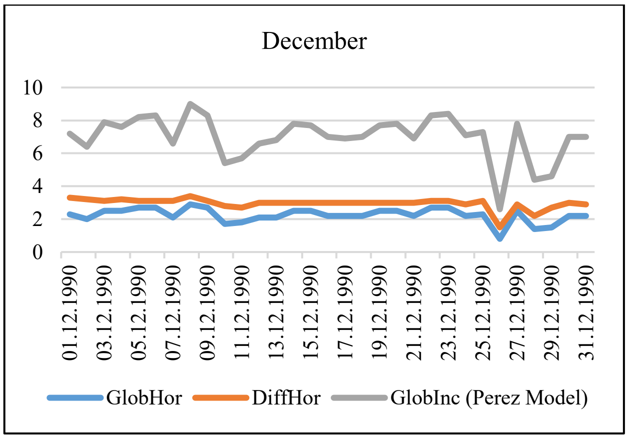
B. Solar Irradiation

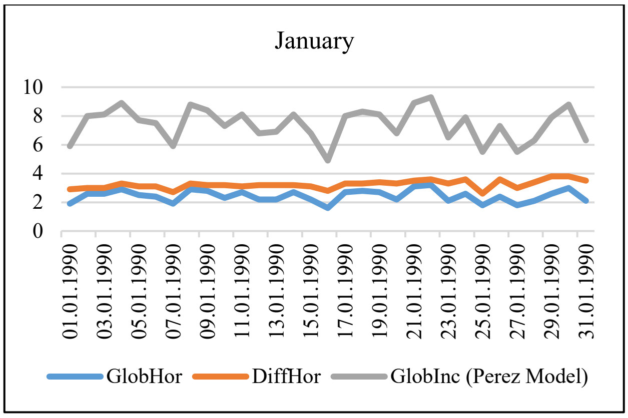
To identify the three consecutive poor sunshine days, monthly (Table 1) and daily (Fig. 4) GHI data of the selected region has been analyzed. Based on the winter months daily GHI data and PV production under 30^0 tilted angle we have identified the 3 consecutive poor sunshine days being November 11-13th.

TABLE III. MONTHLY IRRADIATION VALUES FOR HOVUSLU REGION

	GlobHor	SOC	Pr_LOL	E_Miss	E_User	E_Load	E_Avail
	kWh/m^2	ratio	%	kWh	kWh	kWh	kWh
Jan	75.6	0.909	0	0	120.3	120.3	284.5
Feb	83.4	0.094	0	0	107.3	107.3	254.2
Mar	124.3	0.94	0	0	121.5	121.5	325
Apr	149	0.94	0	0	114.8	114.8	326.1
May	184.4	0.941	0	0	117.5	117.5	372
Jun	209.1	0.941	0	0	113.5	113.5	401.9
Jul	195.6	0.941	0	0	124	124	374.6
Aug	180.3	0.941	0	0	119	119	375.7
Sep	140	0.941	0	0	113.9	113.9	334.3
Oct	105.7	0.94	0	0	114.4	114.4	290.5
Nov	76.4	0.93	0	0	113.7	113.7	258.1
Dec	69.5	0.938	0	0	119.7	119.7	276.4
YEAR	1593	0.936	0	0	1400	1400	3884







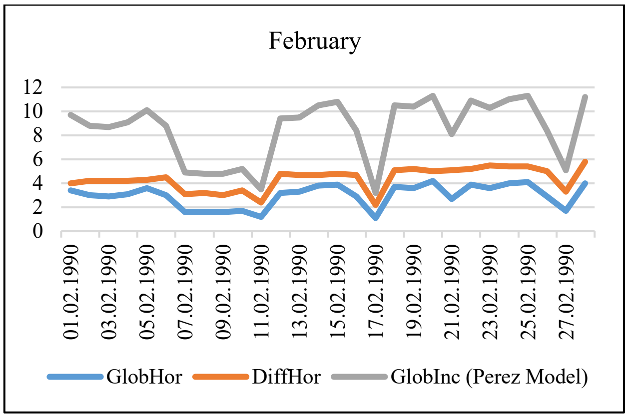


Fig. 4. GHI, DHI and GlobInc Daily Values

C. *Variable Load Profile Construction*

The construction of variable load profiles in this study utilized PVSyst software version 7.3. The profiles were generated to reflect realistic residential energy consumption patterns under varying conditions. Three distinct load profiles were modelled:

Profile 1: A steady profile with moderate variability, designed to simulate typical household routines.

Profile 2: A moderately variable profile, incorporating dual peak consumption periods.

Profile 3: A highly stochastic profile with significant unpredictability, representing irregular energy usage.

The load profiles were developed based on probability-driven algorithms embedded in PVSyst. These algorithms utilize inputs such as daily energy demand, appliance usage schedules, and stochastic factors to simulate variability. The probability distributions applied include:

$$E_{Load}(t) = \sum_{i=1}^{n} P_i(t)\,\Delta t \qquad (4)$$

where:

E_{Load}: Energy demand at time t,

$P_i(t)$: Power usage of the appliance at time t,

Δt: Time interval for load recording.

Key parameters such as average daily energy consumption (9 kWh) and seasonal variations were input to ensure alignment with real-world conditions.

In Fig. 5, we present and analyze three variable residential load profiles as described. These profiles are critical for understanding the energy consumption patterns in residential buildings, particularly in the context of designing an efficient photovoltaic (PV) system for the Zangilan region in Azerbaijan.

Comparison and Implications comparing the three profiles, several key differences and similarities emerge:
Profile 1 has the most stable daily consumption, while Profile 3 shows the highest variability. Profile 2 falls in between, with moderate variability. In Profile 1, the load distribution is more concentrated in the evening, aligning with typical residential consumption patterns. Profile 2 spreads the load more evenly across the day with two distinct peaks, while Profile 3 shows a more erratic distribution, making it less predictable.

Profile 1 likely represents a typical household with consistent evening energy use, while Profile 2 may correspond to households with more varied daily routines. Profile 3 might represent a scenario with less predictable behavior, possibly due to factors like irregular work hours or fluctuating occupancy levels.

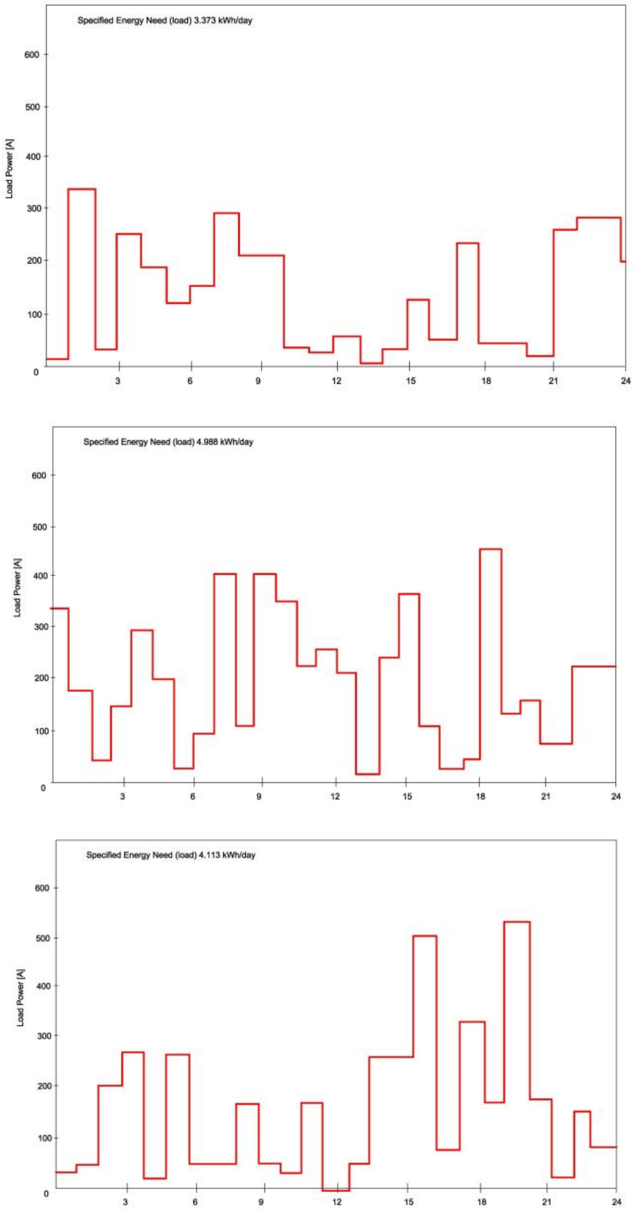


Fig. 5. Variable Load profiles

The variability in these profiles underscores the importance of carefully sizing the PV system to ensure it can meet the load demands effectively.

III. RESULTS AND DISCUSSIONS

The results of simulation on PVSyst software they are described in Fig. 6. A PR of 0.3 means that the actual energy output of the system is only 30% of what would be expected under standard conditions. A PR of 0.3 indicates that the system is not performing optimally and is experiencing significant energy losses. This can result in lower energy production and reduced economic returns on the investment in the system. Even if the system covers the required energy demand by the user, as the solar friction is 1, the system has 60% of loss in the battery that leads the system to low performance.

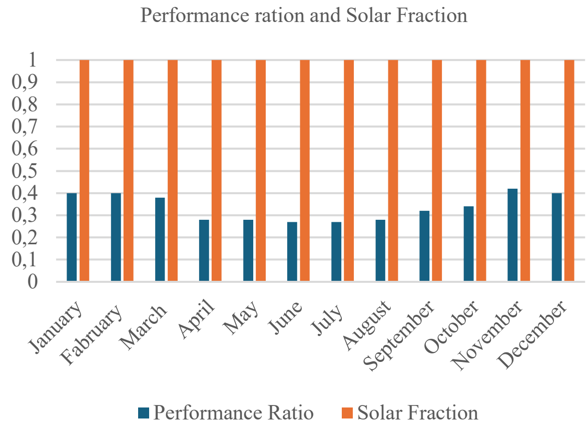


Fig. 6. Performance ratio and solar friction

The battery charging and discharging currents curves (Fig. 7) for the poor sunshine dates shows that the charging current is less than discharge current. It means that the battery is not being charged at a fast enough rate to fully restore its energy while it is being used. This can lead to the battery gradually losing its capacity over time, as it is not being fully recharged during each charging cycle. If the battery is being discharged at a rate that is higher than the charging current, it can also lead to the battery being drained faster than it can be charged, which can result in a shorter overall lifespan for the battery.

It is also important to regularly monitor the battery's state of charge (Fig. 8). The charging current and discharging current can have a significant impact on the state of charge (SOC) of a battery. If the charging current is less than the discharging current, the SOC of the battery will gradually decrease over time, as the battery is not being fully recharged during each charging cycle.

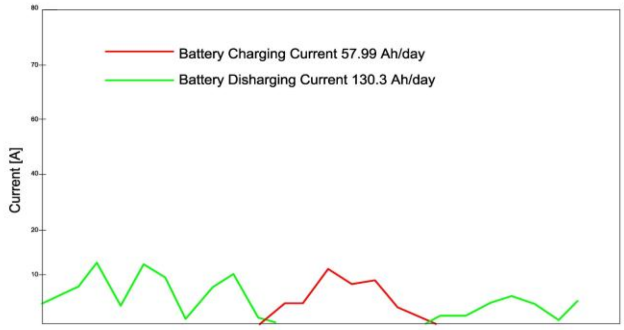


Fig.7. Battery charge and discharge current

To optimize the SOC of a battery, it is important to avoid overcharging or undercharging the battery. Regular monitoring of the battery's state of charge and condition can also help to ensure that the battery is being properly maintained and optimized for its intended use.

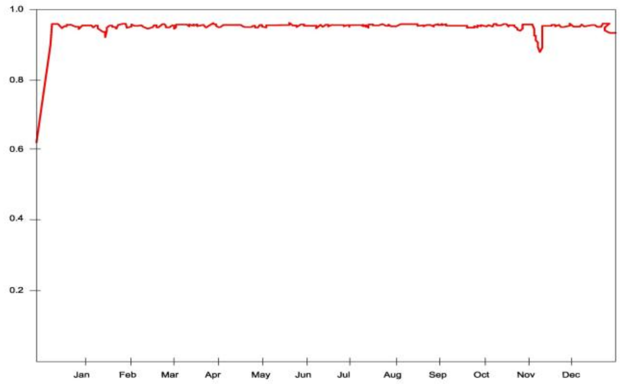


Fig. 8. Battery state of charge distribution

The analysis of battery performance revealed significant seasonal variations in charging and discharging cycles due to differences in solar energy availability. Fig. 9 presents the battery's state of charge (SOC) over a week during summer and winter. In summer, the SOC demonstrates higher levels of charge and discharge due to abundant sunlight, allowing the system to maintain better energy reserves. In contrast, winter cycles show reduced charging efficiency, reflecting the lower solar irradiance during this season. This comparison underscores the importance of designing battery systems capable of adapting to seasonal energy dynamics to ensure system reliability.

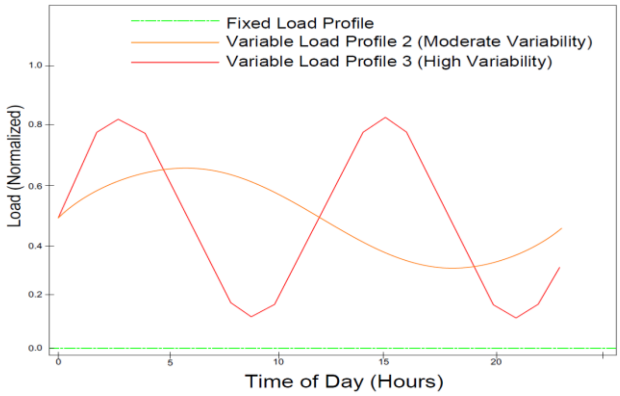


Fig. 9. Battery Charge-Discharge Cycles Across Seasons

These findings emphasize the challenges posed by unpredictable load patterns, as they directly impact system stability and energy efficiency. Addressing load variability is critical for optimizing system performance and ensuring consistent operation, especially in regions where load fluctuations are prevalent.

IV. CONCLUSION

The article provided a simulation of off-grid PV system under uncertain load profile and analyzed its impact on system performance and battery life cycle. The analysis of random load fluctuations reveals that adhering to the load profile is essential regardless of constraints. Even a minor increase in load demand can potentially lead to power shortages in the system. Especially, where the number of electric vehicles is increasing in the world the topic is becoming more crucial.

Monitoring the performance ratio and battery SOC in off-grid PV systems is important to ensure that the system is operating efficiently, and that there is sufficient energy reserves to meet the household's energy demands. By monitoring these metrics, system owners and installers can identify potential problems and optimize the system for maximum efficiency and reliability.

The observed performance ratio of 81% and favorable battery SOC levels highlight the system's capability for long-term reliability and efficiency, particularly in regions with similar climatic conditions to the study area. These findings align closely with industry benchmarks for renewable energy systems, underscoring their applicability for sustainable energy solutions in remote or off-grid settings.

The results of the study can be used to identify strategies for minimizing the negative effects of load fluctuations. They can be used to inform decision-making around the installation and use of off-grid PV systems for residential applications.

The study's insights into the impact of load fluctuations on off-grid PV systems can be used to inform broader policy and regulatory discussions around the deployment of renewable energy systems in residential settings. By highlighting the challenges posed by load fluctuations and offering potential solutions, the study can help policymakers and regulators develop policies and regulations that support the widespread adoption of residential renewable energy systems. It is specifically relevant for Azerbaijan Republic energy transition period where a huge amount of renewable energy penetration is planned.

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