



Qayta tiklanuvchi energiya manbalarining taqsimlash tarmoqlaridagi energiya isroflariga ta'sirini tahlil qilish

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Dolzarbli: : quyosh fotoelektr va shamol generatsiyasining taqsimlash tarmoqlariga jadal integratsiyalanishi quvvat oqimlarining an'anaviy bir yo'nalishli tuzilishini o'zgartirmoqda. Past va o'rta penetratsiyada mahalliy generatsiya liniya toklarini va I²R isroflarini kamaytirishi mumkin, biroq yuqori penetratsiyada teskari quvvat oqimi va kuchlanishning ortishi ayrim uchastkalarda isroflarni qayta oshirishi mumkin. Shu sababli QTEMning isroflarga ta'sirini ish rejimi va boshqaruv vositalari bilan birgalikda baholash dolzarbdir.

Maqsad: qayta tiklanuvchi energiya manbalarining taqsimlash tarmoqlaridagi energiya isroflariga ta'sir mexanizmlarini aniqlash, xalqaro tadqiqotlarda keltirilgan miqdoriy natijalarni qiyosiy baholash hamda hosting capacity, kuchlanish profili va talabni boshqarish o'rtasidagi bog'lanishni tahlil qilish.

Usullari: qayta tiklanuvchi energiya manbalarining taqsimlash tarmoqlaridagi energiya isroflariga ta'sirini miqdoriy baholash uchun IEEE 33- va 123-tugunli test tizimlari hamda real past kuchlanishli tar-moqlarda olingan natijalar o'zaro solishtirildi. Aktiv quvvat isroflari I²R va branch-flow bog'lanishlari asosida baholandi. QTEM penetratsiyasi, hosting capacity, kuchlanish og'ishi va demand response asosiy qiyosiy ko'rsatkichlar sifatida qabul qilindi. Ochiq e'lon qilingan sonli jadvallar asosida kuchlanish profili, hosting capacity-isrof bog'lanishi va demand response-isrof sezgirligi grafiklari qayta qurildi.

Natijalar: QTEMning isroflarga ta'siri nochiqli va ish rejimiga bog'liq ekani aniqlandi. Meng va boshq. ishida tarmoq isroflari 3,88 % ga kamaygan. Loji va boshq. natijalarida demand response C6 holatida isrofni 1471,68 dan 1248,63 kWh gacha kamaytirgan, 18-tugundagi minimal kuchlanish esa 0,9141 dan 0,9327 p.u. gacha yaxshilangan. Demand re-sponse ishtiroki 0-30 % oralig'ida isrofni 1489,95 dan 1273 kWh gacha kamaytirgan.

Kalit so'zlar: qayta tiklanuvchi energiya manbalari, taqsimlash tarmog'i, energiya isroflari, fotoelektr generatsiya, teskari quvvat oqimi, hosting capacity, demand response, kuchlanish profili.

Анализ влияния возобновляемых источников энергии на потери электроэнергии в распределительных сетях

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Актуальность: интеграция фотоэлектрической и ветровой генерации изменяет однонаправленную структуру потоков мощности в распределительных сетях. При низкой и умеренной доле ВИЭ локальная генерация может снижать токи и потери I²R, однако при высокой доле возможны обратные перетоки и повышение напряжения, из-за чего потери на отдельных участках могут снова возрастать. Поэтому влияние ВИЭ необходимо оценивать с учетом режима сети и средств управления.

Цель: выявить механизмы влияния возобновляемых источников энергии на потери в распределительных сетях, сопоставить количественные результаты современных международных исследований и проанализировать взаимосвязь между hosting capacity, профилем напряжения и управлением спросом.

Методы: для количественной оценки влияния возобновляемых источников энергии на потери в распределительных сетях сопоставлены результаты, полученные на IEEE 33- и 123-узловых тестовых системах и реальных низковольтных сетях. Потери активной мощности оценивались на основе зависимостей I²R и branch-flow. В качестве основных показателей сравнения использованы уровень проникновения ВИЭ, hosting capacity, отклонение напряжения и demand response. По опубликованным числовым таблицам реконструированы графики профиля напряжения, зависимости hosting capacity-потери и чувствительности потерь к участию demand response.

Результаты: влияние ВИЭ на потери имеет нелинейный и режимно-зависимый характер. Meng и соавт. получили снижение потерь на 3,88 %. По данным Loji и соавт., demand response в случае C6 уменьшил потери с 1471,68 до 1248,63 kWh, а минимальное напряжение в узле 18 повысилось с 0,9141 до 0,9327 p.u. При росте участия demand response от 0 до 30 % потери снизились с 1489,95 до 1273 kWh.

Ключевые слова: возобновляемые источники энергии, распределительная сеть, потери энергии, фотоэлектрическая генерация, обратный поток мощности, hosting capacity, demand response, профиль напряжения.

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Analysis of the impact of renewable energy sources on energy losses in distribution networks

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Relevance: the rapid penetration of solar photovoltaic and wind generation into distribution networks is changing the conventional unidirectional structure of power flows. At low-to-moderate penetration, local generation can reduce upstream power transfer, feeder current and I²R losses. At high penetration, however, reverse power flow, voltage rise and reactive-power exchange can cause losses to increase again in some feeder sections. The effect of renewable energy sources on network losses should therefore be evaluated together with operating conditions, generation siting and available control resources.

Aim: to identify the mechanisms through which renewable energy sources affect energy losses in distribution networks, compare verified quantitative results reported in recent international studies, and analyze the relationship among hosting capacity, voltage profile and demand response.

Methods: to quantify the effect of renewable energy sources on distribution-network energy losses, results reported for IEEE 33- and 123-bus test systems and real low-voltage networks were compared. Active-power losses were evaluated using I²R and branch-flow relationships. RES penetration, hosting capacity, voltage deviation, and demand-response participation were used as the principal comparison indicators. Published numerical tables were used to reconstruct the voltage profile, the hosting-capacity-loss relationship, and the sensitivity of network losses to demand-response participation.

Results: the analysis shows that the effect of renewable energy sources on energy losses is nonlinear and operating-regime dependent. Meng et al. reported a 3.88% reduction in network losses under coordinated voltage control. In the results of Loji et al., demand response reduced losses in case C6 from 1471.68 to 1248.63 kWh, while the minimum voltage at bus 18 improved from 0.9141 to 0.9327 p.u. Increasing demand-response participation from 0 to 30% reduced losses from 1489.95 to 1273 kWh. These results indicate that increasing renewable generation alone is insufficient at high penetration levels; coordinated voltage and flexibility control is required.

Keywords: renewable energy sources, distribution network, energy losses, photovoltaic generation, reverse power flow, hosting capacity, demand response, voltage profile.

1. Introduction

Distribution networks were originally designed to deliver power from centralized generation to end users. With the deployment of distributed photovoltaic and wind generation, some feeders increasingly operate with bidirectional power flows. This transition can reduce upstream power transfer, but it also introduces new voltage and thermal constraints, particularly when renewable generation exceeds local demand.

The effect of renewable energy sources (RES) on network losses should not be interpreted as unidirectional. At low or moderate penetration levels, local generation reduces the power imported from the upstream grid and decreases feeder current. Because conductor losses are proportional to the square of current, this may lower active-power and energy losses. At higher penetration levels, however, reverse power flow may develop; voltage rise and additional reactive-power exchange can then increase current in some feeder sections and partially offset the initial loss reduction.

The purpose of this study is to synthesize, from both physical and quantitative perspectives, the impact of RES on energy losses in distribution networks. Particular attention is given to the interaction among RES penetration, voltage profile, hosting capacity and demand response, using verified numerical results from recent international studies rather than generic qualitative statements.

2. Methods and materials

Loss model and physical interpretation. The active-power loss in a branch of a radial distribution network is proportional to the square of the current:

$$P_{\text{loss}, ij} = R_{ij} I_{ij}^2 = \frac{R_{ij} (P_{ij}^2 + Q_{ij}^2)}{V_i^2} \quad (1)$$

The total active-power loss of the network can be expressed as the sum of branch losses:

$$P_{\text{loss}} = \frac{\sum_{i,j \in L} R_{ij} (P_{ij}^2 + Q_{ij}^2)}{V_i^2} \quad (2)$$

For daily or annual assessment, energy losses should be evaluated by accounting for the duration of the operating states:

$$W_{\text{loss}} = \sum_t P_{\text{loss}(t)} \Delta t \quad (3)$$

For a local bus, a simplified active-power balance can be written as:

$$P_{\text{grid}} + P_{\text{RES}} = P_{\text{load}} + P_{\text{loss}} \quad (4)$$

If P_{RES} supplies part of the load, both P_{grid} and feeder current decrease. If P_{RES} exceeds local demand together with the corresponding losses, the sign of P_{grid} changes and reverse power flow begins. The voltage operating condition must simultaneously satisfy:

$$V_i^{\min} \leq V_i \leq V_i^{\max} \quad (5)$$

Table 1. Main mechanisms through which RES integration affects network losses

Operating condition	Physical process	Expected impact on losses	Limiting factor
Low-to-moderate penetration	Local demand is supplied by local generation	Feeder current and I ² R losses decrease	Generation siting and load level
High penetration	Reverse power flow occurs	Current and losses may increase again in some feeder sections	Voltage and thermal limits
Insufficient reactive-power control	Reactive-power flow and voltage deviation increase	Additional losses due to higher current	Inverter reactive-power capability, OLTC, capacitor banks
Mismatch between generation and demand	Time-dependent surplus/deficit power flows	Daily energy losses may increase	BESS, demand response, curtailment
Network reconfiguration	Power flows are re-distributed among feeder branches	Potential reduction in losses	Switching and protection constraints

Study selection and comparative analysis.

The methodological procedure comprised four stages. First, peer-reviewed studies reporting explicit numerical results on the impact of RES or distributed generation on distribution-network losses were selected. Second, the network type, RES/control configuration, hosting capacity, voltage indicators and reported loss values were extracted. Third, relative changes in losses were recalculated where the source data allowed direct verification. Fourth, published numerical tables were converted into comparable plots of bus-voltage profile, hosting-capacity-loss trade-off and demand-response sensitivity. This procedure was used to preserve the original numerical evidence while presenting the results in a uniform analytical form.

Table 2. Comparative characteristics of selected international studies from the perspective of energy losses

Source	Network/test system	RES / control	Main indicator	Verified result
Meng et al., 2024 [6]	IEEE 33- and 123-bus	PV + OLTC + capacitor banks + inverter	P_loss, voltage	Losses reduced by 3.88%; LinDistFlow computation speed increased by 72.2%
Fang et al., 2024 [7]	IEEE 33-bus	PV + wind, source-load uncertainty	DG penetration	DG penetration increased by 23% when correlation-aware planning was applied
Loji et al., 2025 [8]	IEEE 33-bus	PV + demand response	HC, Loss, VDev	C6: 1471.68 → 1248.63 kWh; C7 with DR: 1314.86 kWh
Li et al., 2025 [9]	IEEE 33-bus	GAN-assisted DRO + DG planning	Loss, voltage stability	Compared with the conventional model, losses decreased by 15% and voltage stability improved by 20%
Koirala et al., 2024 [10]	Real large-scale LVDS	Stochastic PV hosting capacity	HC, voltage, thermal limits	Stochastic HC was on average 20% higher than the deterministic estimate
Mulenga et al., 2021 [11]	Three real LV networks	PV uncertainty	Hosting capacity	Separate effects of aleatory and epistemic uncertainty on HC were demonstrated

3. Results and discussion

The impact of RES on energy losses cannot be separated from the voltage operating regime. At high PV penetration, the probability of overvoltage at remote feeder buses increases; in other operating states, weak voltage support and long feeder length can produce low-voltage conditions. Coordinated demand-side and voltage-control actions can therefore affect both the voltage profile and network losses.

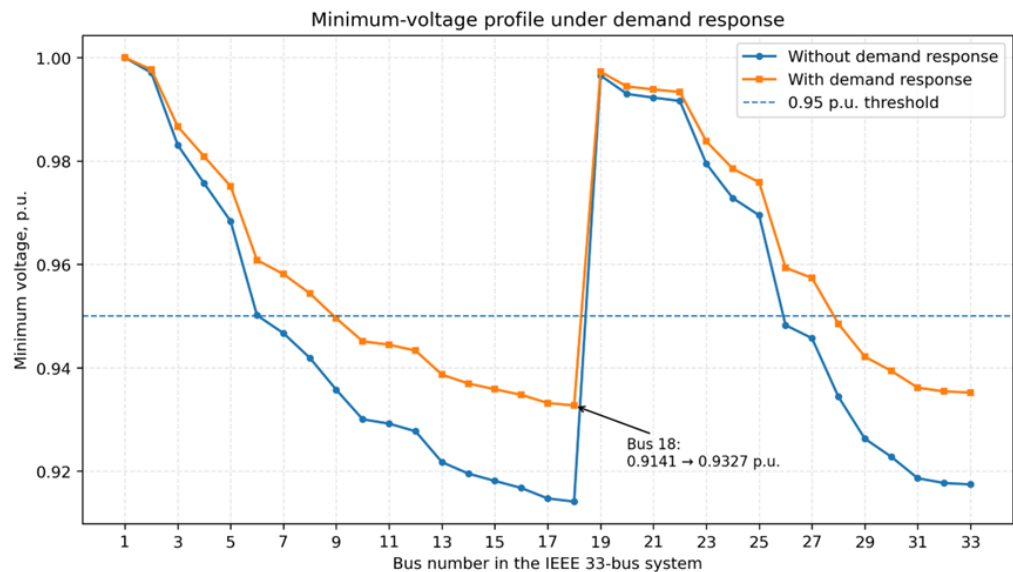


Fig. 1. Change in the minimum-voltage profile of the IEEE 33-bus system under demand response. Reconstructed from the numerical data reported by Loji et al. [8], Table 18.

According to the data reported by Loji et al. [8], the minimum voltage at bus 18 increased from approximately 0.9141 to 0.9327 p.u. when demand response was applied. The improvement is not limited to one bus; the entire lower-voltage segment of the feeder shifts upward. This illustrates why loss analysis in RES-rich networks should be accompanied by voltage-profile assessment rather than treated as an isolated scalar indicator.

Hosting-capacity and energy-loss trade-off.

PV hosting capacity characterizes the amount of additional photovoltaic generation that a network can accommodate without violating technical constraints. Maximizing hosting capacity does not automatically minimize losses, because a larger local generation capacity can create reverse power flows and voltage constraints at specific operating times. A meaningful assessment therefore requires simultaneous consideration of hosting capacity, losses and voltage deviation.

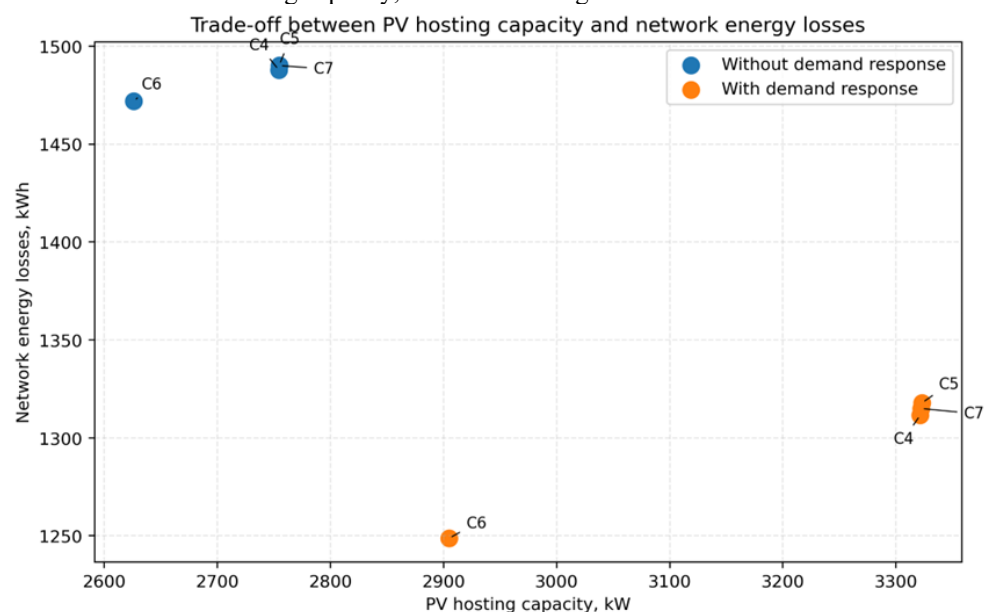


Fig. 2. Trade-off between PV hosting capacity and network energy losses for cases C4-C7. Reconstructed from the numerical data reported by Loji et al. [8], Table 4.

With demand response, the C4-C7 operating points generally shifted toward higher hosting capacity and lower energy losses. In case C6 (Loss + VDev), losses decreased from 1471.68 to 1248.63 kWh, corresponding to a reduction of approximately 15.16%. These results show that flexibility on the demand side can alter the feasible operating region of a RES-rich feeder and improve the energy-loss outcome without simply reducing installed PV capacity.

Demand response and other control resources.

Reducing losses associated with RES integration does not necessarily require changing the generation capacity itself; adapting the load profile and network operating regime can also be effective. Demand response shifts part of the consumption toward periods of high local generation, thereby reducing surplus export and feeder current.

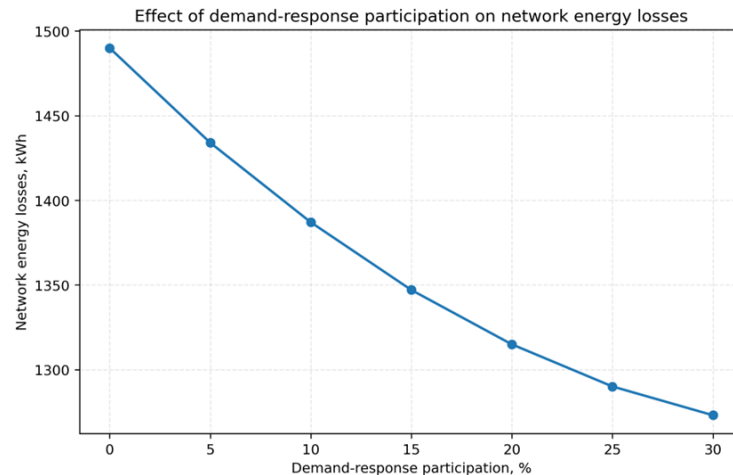


Fig. 3. Effect of increasing demand-response participation on network energy losses. Reconstructed from the numerical data reported by Loji et al. [8], Table 19.

For the data reported by Loji et al. [8], increasing demand-response participation from 0 to 30% reduced network energy losses from 1489.95 to 1273 kWh, or by approximately 14.56%. Although this quantitative result pertains to one test system, it illustrates the broader role of flexibility resources in limiting reverse power flows and improving energy efficiency under high RES penetration.

Table 3. Main control resources for reducing losses under RES integration

Control resource	Mechanism of action	Effect on losses	Main limitation
Demand response	Shifts demand toward periods of high RES generation	May reduce reverse power flow and feeder current	Consumer participation and comfort constraints
PV inverter Q-control	Provides local reactive-power compensation	May reduce reactive-power flow and current	Inverter apparent-power limit
OLTC	Adjusts feeder voltage level	Indirect effect through improved voltage operating conditions	Frequent switching is undesirable
Capacitor bank	Provides reactive-power compensation	Reduces reactive-power flow and I ² R losses	Discrete steps and risk of overcompensation
BESS	Shifts surplus RES energy in time	Reduces peak and reverse power flows	Cost, degradation, and state-of-charge constraints
Network reconfiguration	Redistributes power-flow paths	Relieves heavily loaded branches	Protection and switching constraints

Interpretation of the results.

The reviewed studies make it possible to describe the effect of RES on distribution-network losses in three stages. In the first stage, local generation reduces active-power flow and conductor losses because part of the demand is supplied close to the load. In the second stage, as penetration increases, voltage constraints, reactive-power exchange and reverse power flow become more relevant. In the third stage, the loss outcome is increasingly determined by the availability and coordination of flexible resources such as demand response, inverter reactive-power control, OLTC, storage and network reconfiguration.

Accordingly, broad statements such as ‘RES reduces losses’ or ‘RES increases losses’ are insufficient. The outcome depends on feeder topology, RES siting, load density, generation profile, power



factor, voltage constraints and the control strategy. For this reason, quantitative comparisons should be made under consistent load and meteorological conditions and should distinguish active-power losses from time-integrated energy losses.

From a methodological perspective, a particularly informative design for future studies is to increase RES penetration stepwise in the same feeder, for example across 0-20-40-60-80% scenarios, while tracking annual or daily energy losses, minimum and maximum voltage, reverse-power-flow duration and curtailed renewable energy. Such a design would make the turning point between beneficial and adverse RES impacts explicit for a real network.

Table 4. Recommended indicators for subsequent practical studies

Indicator	Notation	Purpose	Recommended time resolution
Energy losses	W_{loss} , kWh	Quantifies the actual energy-efficiency impact of RES	15-60 min / daily / annual
Active-power losses	P_{loss} , kW	Identifies the most severe operating conditions	Peak- and minimum-load states
Minimum/maximum voltage	V_{min} , V_{max}	Assesses voltage-rise/drop risk	Each time step
Reverse-power-flow duration	T_{rev}	Quantifies the effect of surplus generation	Daily / annual
RES penetration	K_{RES}	Enables scenario comparison	0-20-40-60-80%
Curtailed energy	E_{curt}	Quantifies RES energy rejected because of technical constraints	Daily / annual

4. Conclusion

The impact of renewable energy sources on energy losses in distribution networks is nonlinear and strongly dependent on the operating regime. Losses decrease when local generation reduces upstream power transfer and feeder current, but at higher penetration levels reverse power flow, voltage rise and reactive-power exchange can change this tendency.

Quantitative results reported in international studies demonstrate the importance of coordinated control. Voltage/var control those accounts for PV uncertainty achieved a 3.88% reduction in network losses in Meng et al. [6]. In Loji et al. [8], demand response reduced losses from 1471.68 to 1248.63 kWh in the C6 case and improved the minimum voltage at bus 18 from approximately 0.9141 to 0.9327 p.u. Increasing demand-response participation from 0 to 30% reduced losses from 1489.95 to 1273 kWh.

The next practical step should therefore be to compare RES penetration scenarios on a real distribution feeder under the same load and meteorological data, while evaluating daily and annual energy losses together with voltage limits and reverse-power-flow duration. This would provide a network-specific basis for determining the RES penetration range that improves energy efficiency without creating unacceptable operating constraints.

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