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Evaluation of single-phase net metering to meet renewable energy targets: A case study from Pakistan

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ABSTRACT

Net energy metering (NEM) has become a powerful regulatory tool for promoting distributed generation (DG) worldwide. NEM aids utilities in reducing power constraints and line losses and effect positive economic gains by integrating renewable energy sources. In Pakistan, the current NEM market is limited to three-phase users, even though single-phase customers account for 90% of all residential connections, equal to 28 million, and can significantly impact Pakistan's NEM growth. Therefore, the conducted study provides the techno-economic evaluation of NEM for single-phase consumers. The article offered policy proposals to encourage distribution companies (DISCOs) and single-phase customers to adopt NEM to achieve a win-win situation. The technical analysis is conducted to see how the single-phase NEM affects voltage regulation, system unbalances, and line losses. The viability of the current feed-in tariff for single-phase NEM consumers is assessed to analyze the economic impact. The results show that if only 5% single-phase NEM is allowed, 7.54 TWh can be renewably added to the grid, reducing 4.95 Mtonn CO_2 emissions. Furthermore, this paper presents a case study of how the consumer and the DISCOs can benefit from several NEM penetration. The presented analysis and policy recommendations may help Pakistan and other countries with identical socio-demographic profiles.

1. Introduction

Pakistan is ground zero for climate change. The country has faced heat waves, catastrophic floods, smog, and other natural calamities for the past few years. These natural disasters have killed, and displaced thousands destroyed livelihoods, and damaged infrastructure. Climate change raises the prospect that these and other natural hazards will increase in frequency and severity in the coming decades—a stark reminder that Pakistan is one of the countries that are vulnerable to the effects of climate change.

The demand for energy in Pakistan has increased due to the high population growth rate, estimated at 3% per year with a median age of just over 22 years. Population growth has resulted in increased urbanization, a significant increase in automobiles, and some industrial development. Due to this growth, the country's energy demand is growing by more than 9% annually(Irfan et al., 2019). The total energy demand which was 110 TWh in 2018 is forecasted to reach approximately 400 TWh by 2030 under the current government policies and energy mix usage(Raza et al., 2022). The use of fossil fuels like coal, natural gas, oil, and liquefied natural and petroleum gases has grown to accommodate the surging demands in the country's energy sector (Musa et al., 2018; Liu and Xu, 2021; Tahir et al., 2021). About 67% of electrical power generation in Pakistan is through fossil fuels; which produce large quantities of GHG emissions and thus are the most significant contributor to the country's emissions, impacting local air quality and expediting climate change contributions. The CO_2 emissions in Pakistan from fossil fuel-based power plants have doubled over the past two decades (Shahid et al., 2020). In 2019-20 Pakistan's total electrical units generated were 134.7 TWh, out of which fossil fuel-based power plants produced approximately 81.433 TWh. The total CO_2 emission produced in 2019-20 was 55.2 Mtons, i.e., 0.61 kg CO2 per unit. According to the Global Climate Risk Index annual report (2020), Pakistan has lost 0.53 percent per unit GDP (Gross Domestic Product) and has suffered an economic loss worth US$ 3792.52 million due to the chaotic climatic events(David Eckstein et al., 2020). Additionally, Pakistan was ranked as the 8th most-affected country due to climate change in 2022. Also, IQAir 2021 ranked Pakistan's air as the 2nd most polluted (David Eckstein et al., 2019; IQAir. World, 2021). The most practical and effective

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way to eradicate this energy gap and reduce CO_2 emissions is to promote renewable energy on an individual level and raise awareness of how effectively it can be used through net metering. In the context of a developing country, rooftop solar allows small modular private investments, which increase the renewable energy penetration without burdening public funds.

Internationally, most countries are doing their part in climate change mitigation and adaptation. Solar Energy is a popular GHG mitigation technique due to the falling Levelised Cost of Energy (LCOE). By 2024, global distributed solar photovoltaic (PV) is expected to increase to 530 GW (Zappa et al., 2019; Hernandez et al., 2014). According to International Energy Agency (IEA), three-quarters of this growth will come from the commercial and industrial sectors, while one-fourth will come from the residential sector (Gokhale-Welch and Watson, 2019). In recent years, the residential solar industry has seen a tremendous rise. New solar installations persisted even during the Covid-19 pandemic; by 2020, the world had installed 138.2 GW of Solar PV(Zaman et al., 2021; Hosseini, 2020). The top five countries in terms of installed solar power capacity are shown in Fig. 1 (Bulut and Menegaki, 2020). Different business models and policy frameworks have been implemented in these countries to encourage the rapid adoption of solar rooftops (Tongsopit et al., 2016; Burger and Luke, 2017; Bankel and Mignon, 2022). With the assistance of regulations and current policies, the worldwide domestic solar energy market is predicted to develop at a CAGR of more than 10% over the next five years; during this period, the LCOE is expected to reduce by around 15% in the residential sector (Zakeri et al., 2021).

Distributed solar PV in Pakistan addresses high electricity costs, and large system losses, and optimally utilizes favorable sun radiation. Unfortunately, subject to various issues, including a poor policy framework, Pakistan's solar installation growth is gradual, with a total solar PV capacity of 1.09 GW, including utility-scale solar PV (Malik et al., 2020). Pakistan intends to reduce up to 50% (15% unconditional and 35% conditional) of its projected emissions by 2030, as pledged in the Nationally Determined Contribution (NDC), subject to the availability of international funding. Moreover, Pakistan is also targeting to add 60% renewable sources by 2030 to the energy mix (GoP and PAKISTAN, 2021). To achieve this goal, it is critical to shift the existing trajectory of power generation towards less polluting and carbon-neutral alternatives (Nieto et al., 2020). Therefore, Net Energy Metering (NEM) could support solar PV transition smoothly and cost-effectively by utilizing private investments(Heesh, 2021).

NEM is a billing and metering mechanism that allows prosumers to generate energy through RES and utilize it within the specified timeframe (Nikolaidis and Charalambous, 2017). This is implemented by a crediting tool (fed in tariff) in which prosumers earn credit for electricity fed into the grid (Ilham et al., 2020; Saumweber et al., 2021). NEM has been successfully implemented in developed and many developing countries (Smith et al., 2021; Ordóñez et al., 2022; Iliopoulos et al., 2020). Fig. 2 shows the theoretical illustration of the NEM from consumer and utility ends. In addition, NEM can be categorized into two types, i.e., a). Single-Phase, and b). Three-Phase. Single-phase NEM is usually unitized in residential LV networks (KhareSaxena et al., 2020; Ahsan et al., 2021). Similarly, three-phase NEM is generally used in commercial and industrial premises. NEM is typically enabled for single- and three-phase residential consumers via single-phase and three-phase hybrid inverters. Before installation of a single-phase inverter, it must be ensured that the inverter is connected to the phase with the highest load. If the inverter is connected to the phase with the lowest load, phase imbalance will occur, affecting the grid's health and power quality (Ziras et al., 2021). Therefore, installing the single-phase prosumer in the lowest load feeder is necessary. This article's primary focus is the load flow analysis for the single-phase NEM connections with the variable PV distribution.

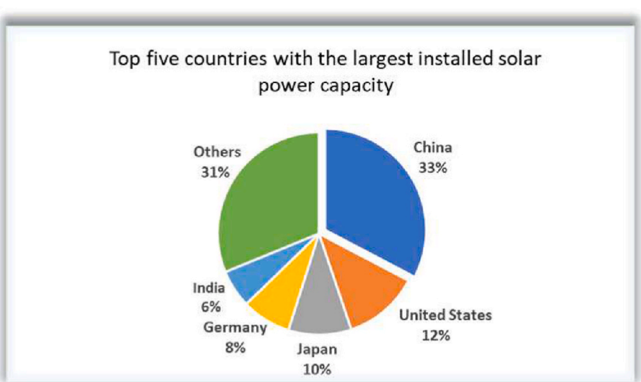


Fig. 1. Top five countries with the largest installed solar power capacity.

Pakistan's National Electric Power Regulatory Authority released the NEM rules and regulations in 2015 under the "Alternative and Renewable Energy Distributed Generation and Net-metering" legislation, under which the government implemented net-metering. As a result, by mid-2021, three-phase NEM connections had grown to a total capacity of 202 MW, around 1% of the coincidental load, as illustrated in Fig. 3.

According to the NEM policy, PV systems with capacities ranging from 1 kW to 1000 kW are permitted; however, a consumer's solar PV capacity cannot exceed 1.5 times the sanctioned load (Shabbir et al., 2020). However, the current policy of NEM only addresses three-phase consumers and thus impedes the going green goal of Pakistan. As a single-phase, consumers constitute 90% of the total residential connection, so it is essential to have a policy that addresses them to meet renewable energy penetration goals. In addition, the high PV penetration in the low voltage (LV) network may cause some power quality challenges (Alquthami et al., 2020). Some of the main issues due to high PV penetration are discussed in the literature, including voltage regulation (Hanif and Choudhry, 2009), voltage rise (Alquthami et al., 2020; Munikoti et al., 2021), power losses (Adefarati and Bansal, 2016), line overloading (Uzum et al., 2020), flicker and harmonics (Ahsan et al., 2021), and reverse power flow (Su et al., 2014). In (Chathurangi et al., 2018) the authors used the urban LV network to pinpoint the problems with power quality. The result showed that high PV penetration violated voltage limitations and increased power loss because of reverse power flow. Similarly, in (Sharma et al., 2020), the authors used data from the 11 kV feeder to show how high PV penetration affects reverse power flow and overvoltage problems. The inverter enters disconnect mode due to the higher PV penetration causing overvoltage problems. However, the situation in Pakistan is different from that of developed countries. Additionally, voltage fluctuations and poor voltage profile happen frequently. The PV penetration at a certain level will help to mitigate this problem.

This article considers voltage regulation and power loss as the two main challenges and provides some beneficial recommendations based on a techno-economic assessment of high PV penetration. In developing countries, the power infrastructure cannot handle high PV penetration. Thus, in this study, a real LV network is simulated to determine the voltage rise and power losses on the network to optimally integrate rooftop PV. The results of the study aim to encourage renewable energy utilization through a single-phase net-metering technique to achieve a win-win situation for both the consumer and the utility company. The paper presents the impact of single-phase NEM on the structure of Pakistan's grid both economically and technically through detailed simulation and financial analysis.

The remaining paper is organized as follows. Section 2 discussed the case study parameters and the methodology employed in the techno-economic analysis. The results of the technical aspect contain the voltage regulation, line losses, and duck curve impact for various scenarios and PV penetration levels in Section 3. Section 4 discussed the economic effect of single-phase NEM on the Disco's revenue loss. The existing and proposed example tariff results are presented to highlight

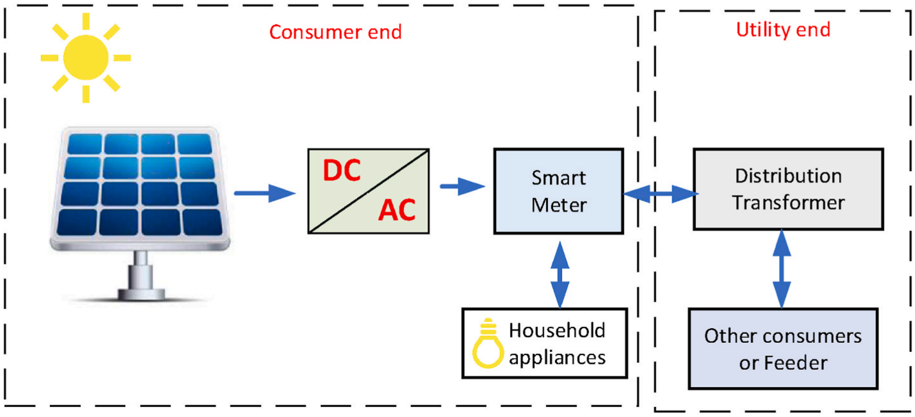
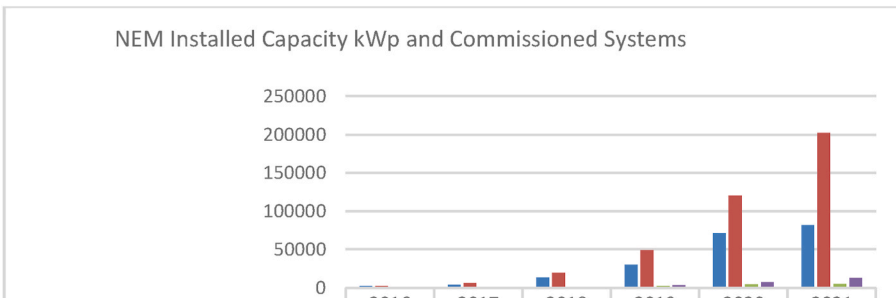


Fig. 2. Schematic illustration for the NEM from both ends: consumer side and utility side.



	2016	2017	2018	2019	2020	2021
Yearly Installed Capccity kWp	2118	3496	13534	29988	71164	81600
Cumulative Installed Capcity in kWp	2188	5684	19218	49206	120370	201970
Yearly Commissioned Systems	40	183	604	2145	4210	4969
Total Commissioned Systems	40	223	827	2972	7182	12151

Fig. 3c. Pakistan's Total Installed net-metered connection till 30th June 2021.

the importance of tariff redesigning to confirm the existence of an unmet positive surplus in the DISCOs revenue. In Section 5, considering the finding and lessons learned from the benchmark state, the paper is concluded with necessary policy interventions and general recommendations in Pakistani and global contexts.

2. Methodology and case study

The paper's main objective is to analyze the possible techno-economic impact of single-phase NEM prosumers in Pakistan, who account for more than 90% of the total domestic connections. Out of eleven DISCOs, Islamabad Electric Supply Company (IESCO) was selected for the case study, where 96% of domestic relations are single-phase. In addition, the actual data of a distribution transformer (DT) connected to a specific IESCO distribution feeder network was collected and simulated using Electrical Transient Analyzer Program (ETAP) for possible scenarios and cases. The load flow analysis is performed to check the viability of the PV system and its impact on the grid side in terms of power quality and losses. In addition, installing the PV system in a massive level produced duck curve problem. So, the impact of a single-phase NEM on the daily load curve for the IESCO distribution network was analyzed, and proposed techniques to mitigate the effects of the duck curve. Later, the financial impact was observed, and the economic viability for the new prosumers in the national grid was proposed. Recommendations have been presented based on carefully plotted results, lessons learned from the benchmark states, interviews with DISCOs' personnel, and software simulation.

2.1. *Case study parameters*

IESCO distribution network is divided into 5 circles, 19 divisions, and 109 sub-divisions. Table 1 displays the sanctioned load (MW) for each category in the IESCO distribution network. In this work, ETAP was used to simulate the load flow with various PV penetration, and the following assumptions are made.

- The power factor of the load is assumed to be 0.95.
- At 1000 W/m^2 solar irradiation, the maximum PV installation per household is the same as the sanctioned load.
- The solar PV generation data for the Islamabad region was calculated using the NREL PVWatts calculator.
- A solar PV installed capacity of 4 kWp per house was considered for the computation and economic evaluation of the duck curve.
- *State of the Industry Report* by the National Electric Power Regulatory Authority of Pakistan was used to estimate the average unit (kWh) rate for the IESCO domestic sector.

Table 1
IESCO's network category-wise sanctioned load (MW).

	Residential	Commercial	Industrial	Agricultural	Public Lighting	Bulk Supply	Others	Total
Category-wise Sanctioned Load (MW)	4698.09	1250.58	1105.28	59.31	101.33	541.48	730.75	8486.82

3. Technical evaluation of single-phase Net Energy Metering

3.1. Modeling of net metering penetration in ETAP for voltage regulation and line losses

The voltage regulation is the critical parameter. Its directly linked to the power losses in the power system. When the voltage drops increase, the consumer side voltage drops. Thus, the overall system losses increased. The voltage regulation is defined as the ratio of the difference between the source and consumer end to the consumer end voltage. eq (1) shows the voltage regulation in the distribution network. And eq (2) shows the line losses due to conductor resistance.

$$Voltage\ Regulation\ in\ (\%) = (V_s - V_r) / V_r * 100\% \quad (1)$$

here.
V_s = Voltage at the source end.
V_r=Voltage at the consumer end

$$Power\ loss = I^2R \quad (2)$$

here.
I= Current in the conductor.
R = Resistance of the conductor.
equations (1) and (2) in the small distribution network are used to find the voltage regulation and power losses. But, in more extensive networks with nonlinear interconnections, iterative techniques such as Newton Raphson, Gauss-Seidel, Fast Decoupled are usually used (Hao et al., 2020). Commercially available software such as Panda Power, Power Factory, PSCAD, and ETAP use the technique as mentioned above to evaluate voltage regulation and line losses in a digitally simulated environment (Agrawal et al., 2016; MATLAB and RTDS, 2016). In this paper, ETAP is used to simulate the IESCO distribution network. The block diagram of IESCO's implemented network is shown in Fig. 4. The distribution transformer (DT) with a rating of 200 kVA and its corresponding load were modeled in the simulation, using the connections data stated in Table 2. A total of fifty-seven houses are distributed to the DT at different phases as per provided data from IESCO. In each phase, nineteen houses are connected. The house that is the farthest away from the DT is 348 m. Due to line losses, the voltage drop on this bus must be more significant than on other buses.

3.1.1. Result and discussion for voltage regulation and line losses

This study looked at six cases, each consisting of five different scenarios based on PV penetration ranging from 0% to 50%. Only one case has one scenario for evaluation of unbalance distribution of PV systems. Each case has different consumption and has other sanctioned loads. Fig. 4 illustrates a schematic diagram of the IESCO distribution network, with actual line lengths and the number of houses connected to each bus.

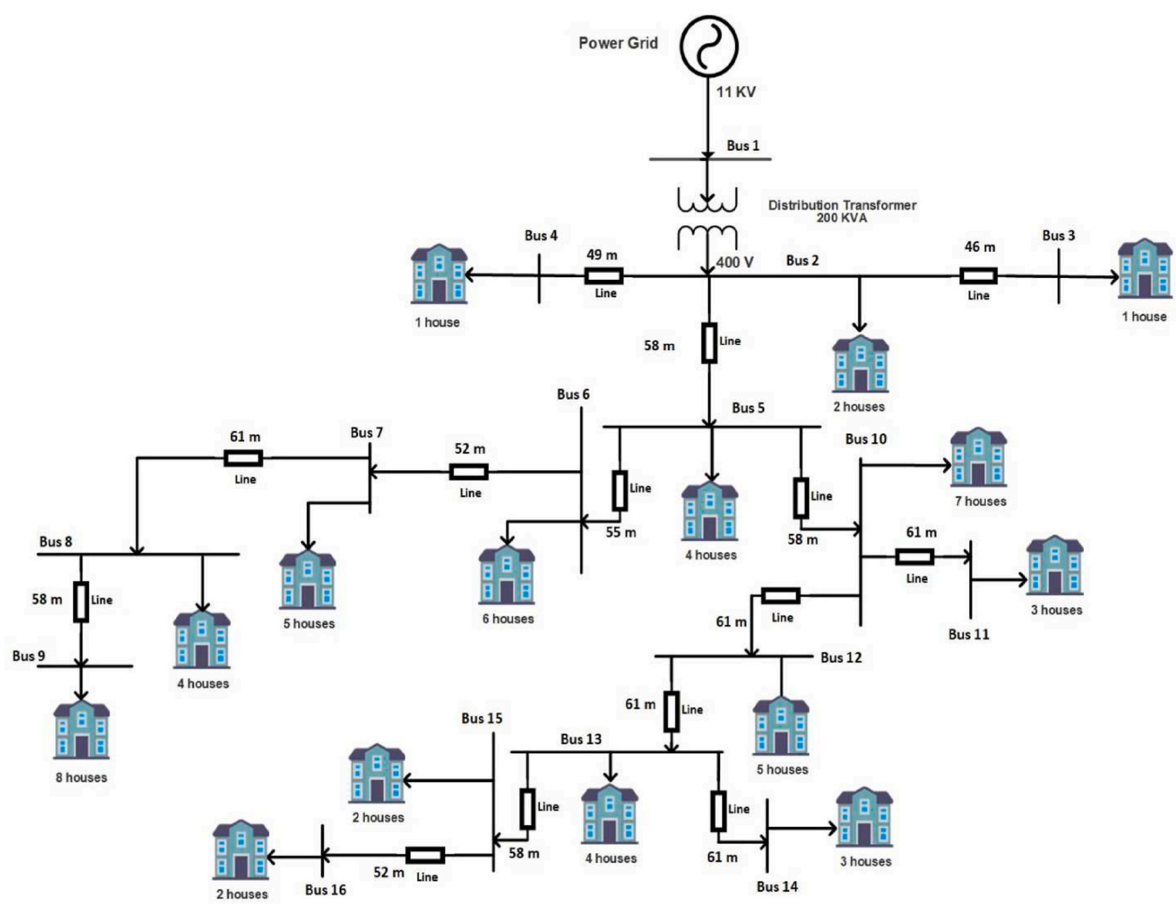


Fig. 4. Block diagram of the IESCO distribution network.

Table 2
Assumed connection scheme, actual length (m), and no. of connected houses.

From Bus	To Bus	Length (m)	No. of Houses	Assumed Phase Connections
1	2	0	2	A B
2	3	46	1	C
2	4	49	1	A
2	5	58	4	B, A, B, C
5	6	55	6	A, B, C, A, B, C
5	10	58	7	A, B, C, A, B, C, C
6	7	52	5	A, B, C, A, B
7	8	61	4	C, A, B, C
8	9	58	8	A, B, C, A, B, C, A, B
10	11	61	3	A, B, C
10	12	61	5	C, A, B, C, A
12	13	61	4	B, A, B, C
13	14	61	3	A, B, C
13	15	58	2	C, A
15	16	52	2	B, C
Total			**57**	**19A, 19B, 19C**

The system comprises 16 buses, each with a specific number of connected single-phase domestic loads. The standard coupling (PCC) voltage regulation was used to compare the different cases. After all the settings in ETAP, the unbalanced load flow study was conducted. In each case, the illustration of the finding and its discussion were addressed individually below.

a. Case A: 0.2–0.4 kVA Load on Each House

Case A represents the winter load scenario of Pakistan. Each household with single-phase winter has a load range of 0.2–0.4 kVA. In this case, the total load connected to DT is 16.7 kVA.

Five scenarios can be considered, with solar PV penetration levels ranging from 0% to 50%. Each household is assumed to have a sanctioned load of 2 kW in this case. At 1000 W/m^2 irradiance, the PV installation per house was assumed to be 2 kWp.

Fig. 5 depicts the per-unit voltage levels at each bus of case A for different scenarios. The figures show that voltage regulation improved as PV penetration rose; however, a voltage rise developed at 50% PV penetration, as seen in Fig. 4 (S5). However, the per-unit voltage increase was under the marginal overvoltage range. In this case, 0–50% PV penetration is not detrimental to the power system because the per-unit voltage is within its limitations.

b. Case B: 1 kVA Load on Each House

In case B, each house has a 1kVA single-phase load. The 200 kVA transformer has a total load of 57 kVA connected to it. Distinct solar PV penetration levels ranging from 0% to 50% are considered in five different scenarios. Each home has a sanctioned load of 1 kW in this scenario. At 1000 W/m^2 irradiance, the average PV installed per house is 1.07 kWp.

Fig. 6 shows that as PV penetration progressed, voltage regulation improved from marginal to 1 p.u. Because the system's per-unit voltage is within its limits, a PV penetration range of 0–50% is not harmful to the power system. This case is only for the middle seasons when load requirements are not so high.

c. Case C: 2 kVA Load on Each House

In case C, each residential single-phase load is 2 kVA. A total load of 114 kVA is connected to the 200 kVA transformer. Five scenarios are considered, with solar PV penetration levels ranging from 0% to 50%. Each home is assumed to have a sanctioned load of 2 kW in this case. At 1000 W/m^2 irradiance, the PV installation per home is assumed to be 2.14 kWp.

Fig. 7 demonstrates that as the PV penetration increased, the voltage regulation improved from marginal Undervoltage to 1 p.u. In this case, 0–50% PV penetration is not detrimental to the system because the per-unit voltage is within its limits. This case covers the middle seasons when the load at each house is intermediate level. In this case, solar PV installation will benefit the power system overall.

d. Case D: 3 kVA Load on Each House

Case D contains 3 kVA residential single-phase loads. The case D represented the summer season when load was high. The 200 kVA transformer has a total load of 171 kVA attached to it. Distinct solar PV penetration levels ranging from 0% to 50% are considered in five different scenarios. Each house is assigned a 3 kW load in this scenario. At 1000 W/m^2 irradiance, the average PV installed per house is 3.21 kWp irradiance.

Fig. 8 illustrates the per-unit voltage values at each bus with different scenarios. The per-unit voltage for the remote buses has decreased to a critical Undervoltage level due to the overloading of the connected load. Fig. 8 Scenario 1 shows the Undervoltage situation in the distribution network. In this case, the high PV penetration will improve the system voltage. The plots show that as PV penetration rise, voltage regulation improves from critical to near-marginal Undervoltage. In this case, a PV penetration of 0–50% has no negative impact on the system because the per-unit voltage increases within its limits.

In this scenario, each household's single-phase demand is in the 2–4 kVA range, assuming it is a summer load in Pakistan. 162.1 kVA is the total load connected to the 200 kVA transformer. Five scenarios may be considered, with solar PV penetration levels ranging from 0% to 50%. Each home is assumed to have a sanctioned load of 2–4 kW in this case. According to their sectioned load, the PV installed per house is 2.23–3.75 kWp randomly at 1000 W/m^2 irradiance.

Fig. 8 depicts the per-unit voltage values at each bus of case e with different scenarios. The per-unit voltage for the remote buses has decreased to a critical undervoltage level due to the overloading of DT. The plots show that as PV penetration rise, voltage regulation improves from critical to near-marginal undervoltage. In this case, a PV penetration of 0–50% has no negative impact on the system because the per-unit voltage increases within its limits.

f. Unbalanced Scenario

To evaluate a situation with unequal solar penetration, a specific case was made in which twenty houses have solar penetration in two phases (A and B), but phase C has none. In this case, each residential single-phase load is assumed to be 2 kVA. A total load of 114 kVA is connected with the DT of 200 kVA. In this case, the solar installed per house is 2.14 kW_p and assume the solar irradiance of 1000 W/m^2. A total of 42.8 kWp of solar was installed in phases A and B. The simulation results are shown is Fig. 9. Fig. 10 depicts the per-unit voltage values at each bus with all phases. The figure demonstrates that the phases' imbalance has been seen due to significant differences in PV penetration between phases. The phase C is in the marginally undervoltage level but the phase imbalance can cause the problems in the generation side and power quality may also influence (Ciontea and Iov, 2021). To avoid this unbalance, the PV must be installed with balance distribution at each phase.

3.1.2. Impact on power loss

Power losses occurred due to various apparatus utilized for generation, transmission, and distribution networks. In this study, the cable and transformer power losses are considered for distribution network. Table 3 illustrates the power loss of the cable, transformer, and total power loss of the system in five cases and scenarios. Active, reactive, and apparent power loss are the three types of power loss considered in this article. The fact is this: the power loss increases when the load increases

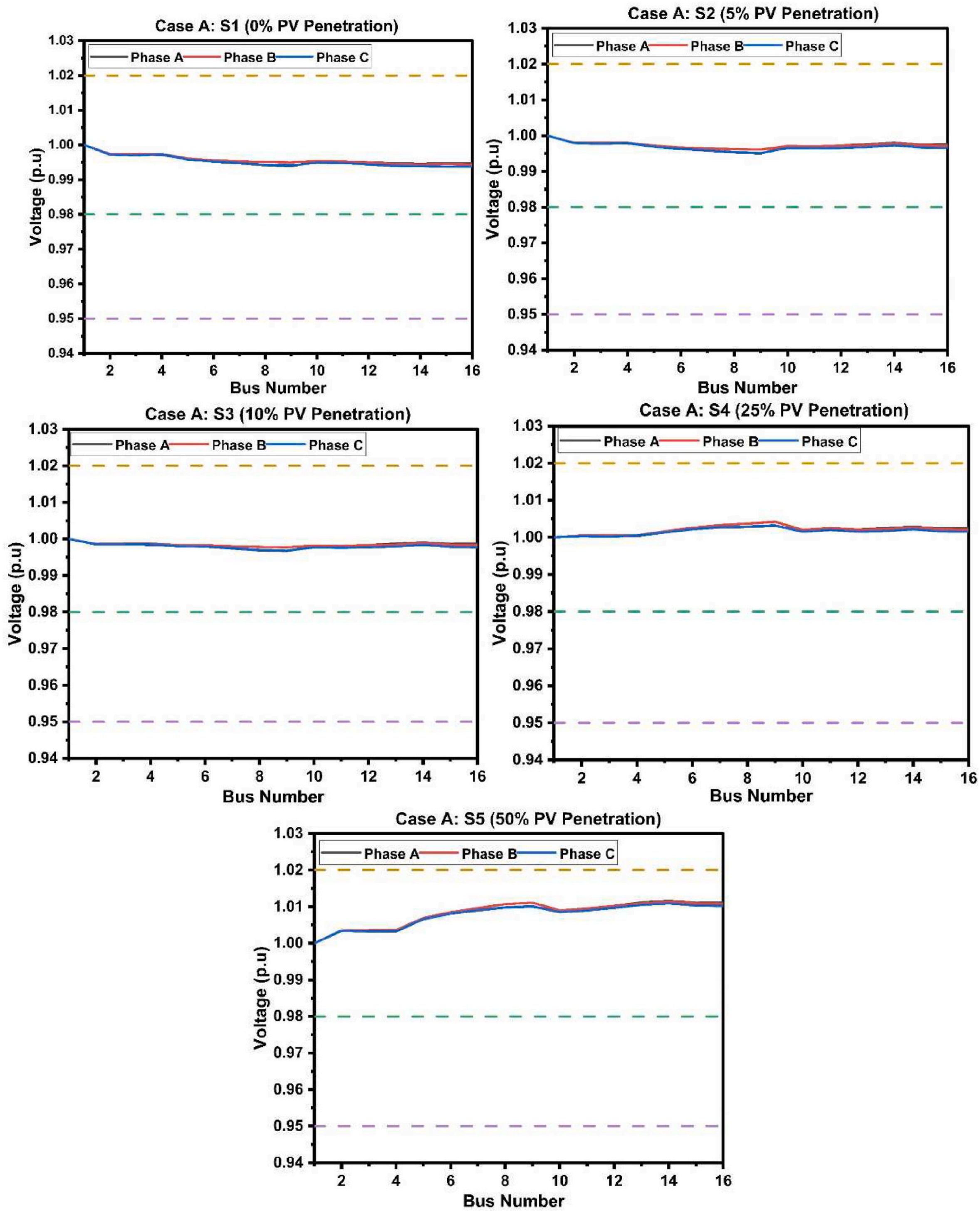


Fig. 5. Case A: System's per unit (p.u) voltage profile with five scenarios from 0 to 50% PV Penetration.

and how far away from the DT. In this case, power losses were reduced from case B to case E with S1 towards S5 owing to load reduction into the power grid, while PV penetration increased from 0 to 50%, as shown in Table 3. In case A, with 50% PV penetration, power losses are higher due to the high PV feed-in compared to other scenarios. In this case, with 50% PV penetration, the power losses are considerable. In all other scenarios and cases, except for case A, power losses are lower at 50% PV penetration relative to S1 (0%) PV penetration scenarios. Similarly, case D with S1 has the highest power loss in the cable and transformer due to the high loading per phase. Therefore, the system's power loss decreases when the DT per phase load is reduced. PV penetration will reduce the overall system's power loss in the following cases and scenarios.

3.1.3. Impact of single-phase Net Energy Metering on load curve

The demand and supply curves of the power sector may be unaffected at lower PV penetration. However, the higher PV penetration has a significant impact on the demand curve. Power sector entities must need to modify their generation capacity as per the PV penetration rises. At the daytime, when PV generation is high, a duck like curve is visible in the demand curve. This phenomenon is called duck curve. The duck

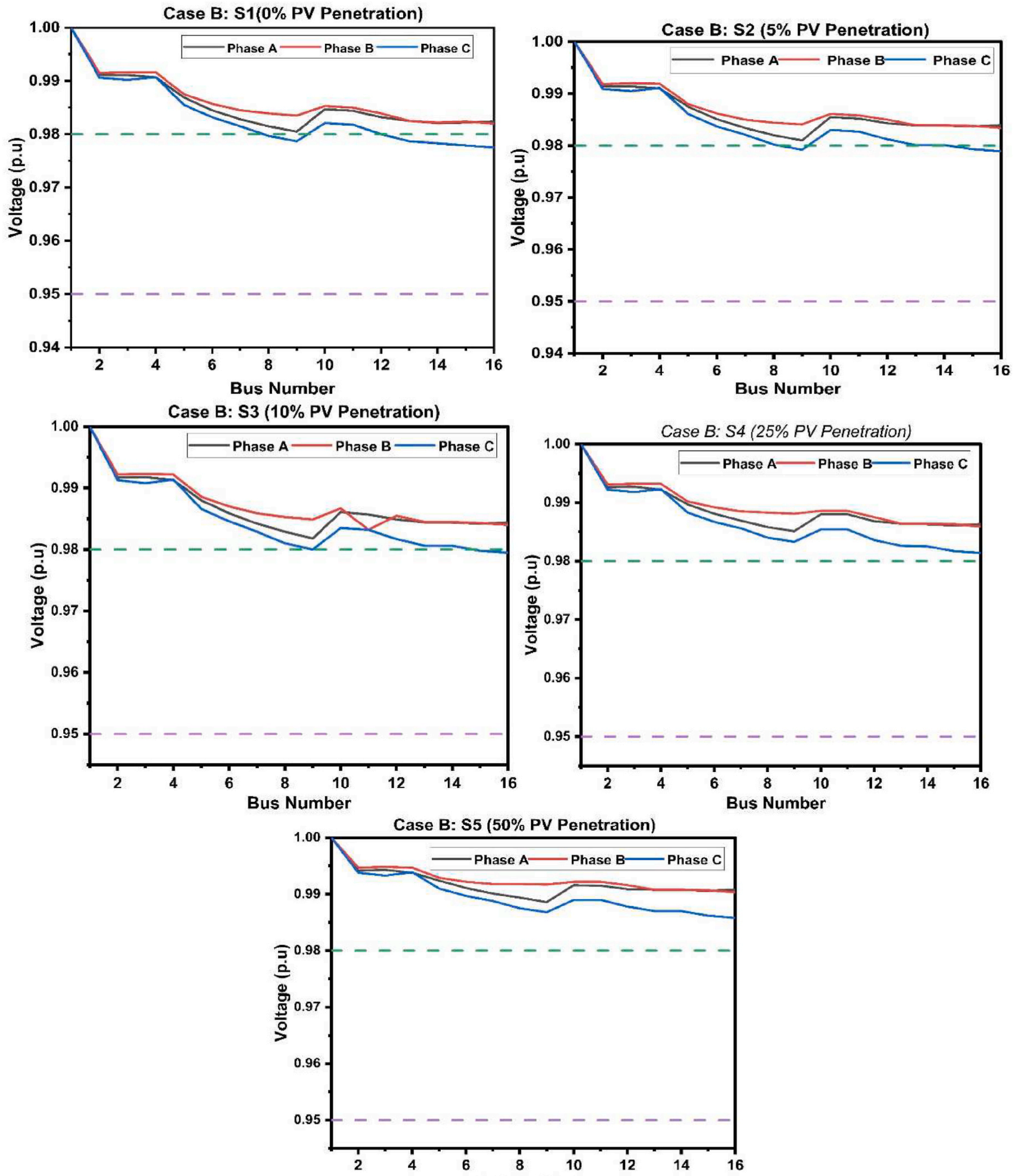


Fig. 6. Case B: system's per-unit (p.u) voltage profile with five scenarios and PV penetration level of 0–50%.

curve of the California is shown in Fig. 11 (Hou et al., 2019). In 2012, the load curve did not include PV penetration. After 2012, when NEM began to add up and duck curve was more visible. The utility company's daytime load is reduced, and as NEM is added year after year, the daytime peak load is reduced even further. However, because the load curve dip occurs only during daylight hours, the load quickly returns to the grid in the evening. The duck curve is a phenomenon where the daytime load curve declines while the evening load curve climbs. The impact of the duck curve varies based on the location of the NEM, the season, penetration, and utility load patterns.

To determine the impact of the duck curve on IESCO's load profile, the estimation of solar PV generation with 5%, 10%, 25%, and 50% of NEM connections in a single phase was considered. The estimated solar PV generation in the IESCO network is represented in Table 4. In this case study, 4 kW of PV installation per house was considered and estimated number of units are calculated based on the NREL PVWatts calculator.

3.2. Duck curve impact on load profiles

To evaluate the impact caused by a large number of single-phase prosumers, the actual load curves of four days in 2019 from four distinct seasons was utilized. Fig. 12 shows the solar irradiance (red curve) in W/m^2 plotted with the load curve (black curve). The NREL PVWatts calculator was used to calculate the solar PV irradiance for the specified days at hourly granularity for Islamabad region. Note that the

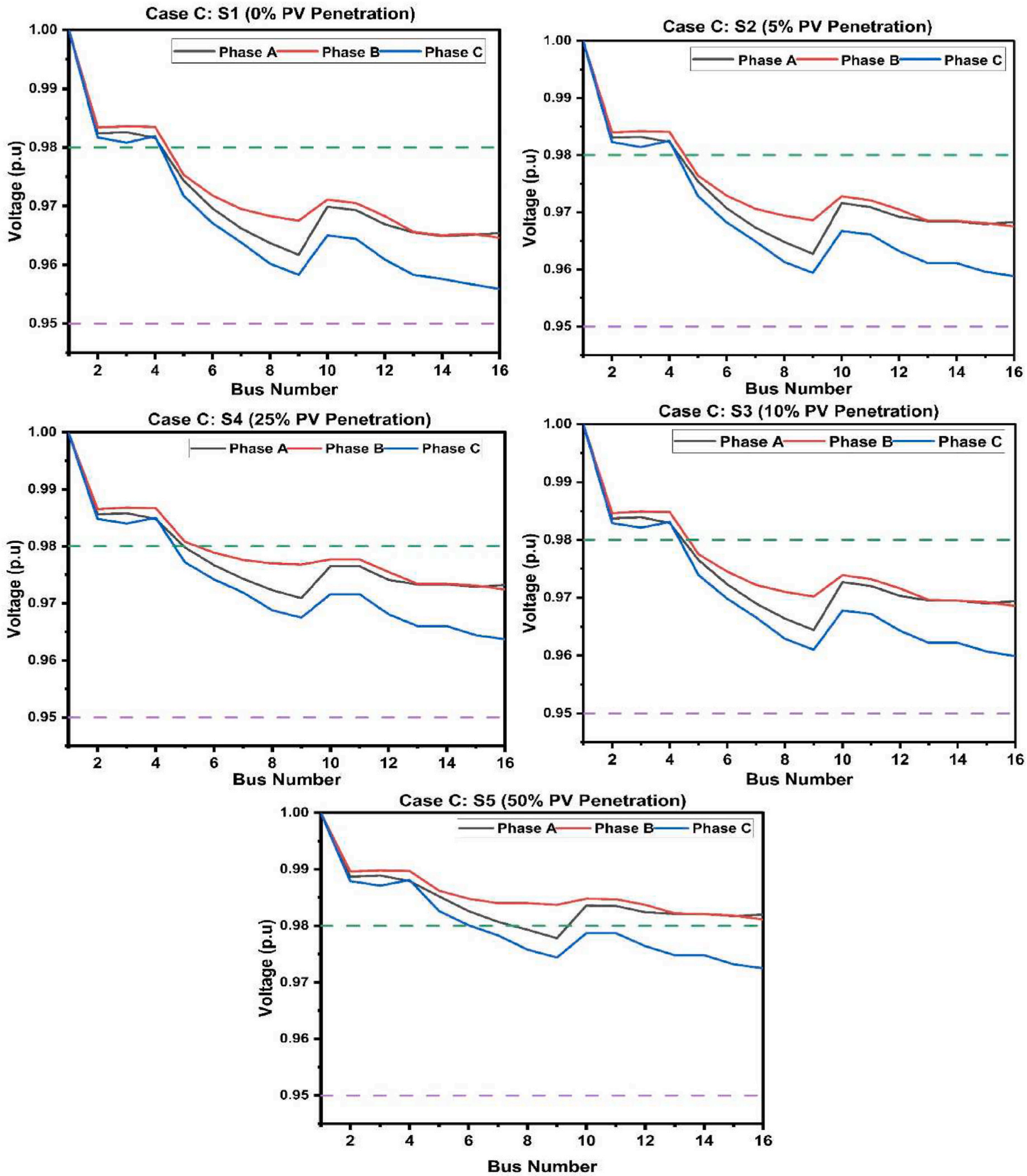


Fig. 7. Case C: System's per-unit (p.u) voltage profile with five scenarios from 0 to 50% PV Penetration.

plotted load curve presents the coincidental load curve. The sanctioned load of IESCO is approximately 4700 MW for domestic customers, but a realistic assessment of the duck curve, the coincidental load profile was employed. The load curve shows that the highest load of four days in IESCO is in summer (June), while the lowest load is in the winter (December).

The impact on load curve with various penetration scenarios is depicted in Fig. 13. The findings shows that the impact of 5% and 10% of NEM penetration reduces the daytime load significantly. While with 25% penetration, the load is negative across all seasons except in September. A 50% penetration reduces the load to negative across all seasons during certain daylight hours. The more important point is that the load must shift rapidly back to the grid in the evening hours. This means that while the daytime load curve changes significantly, the utility company must keep enough generation resources readily available to meet the evening load requirement.

4. Economic viability-evaluation of single-phase Net Energy Metering

The current NEM policy for single-phase prosumers, implemented in January 2021, states that if a single-phase customer wants to enable NEM at their house, they must upgrade to a three-phase connection. Because the consumer is essentially on a three-phase connection after NEM, NEM feed-in is based on a set off-peak FiT of 9.6 cents/kWh. The financial impact of single-phase NEM can be calculated in two ways. "Option 1″ estimates the income loss using a 9.6 cents/kWh off-peak FiT, which is current NEM policy, while "Option 2″ uses a 4.5 cents/kWh

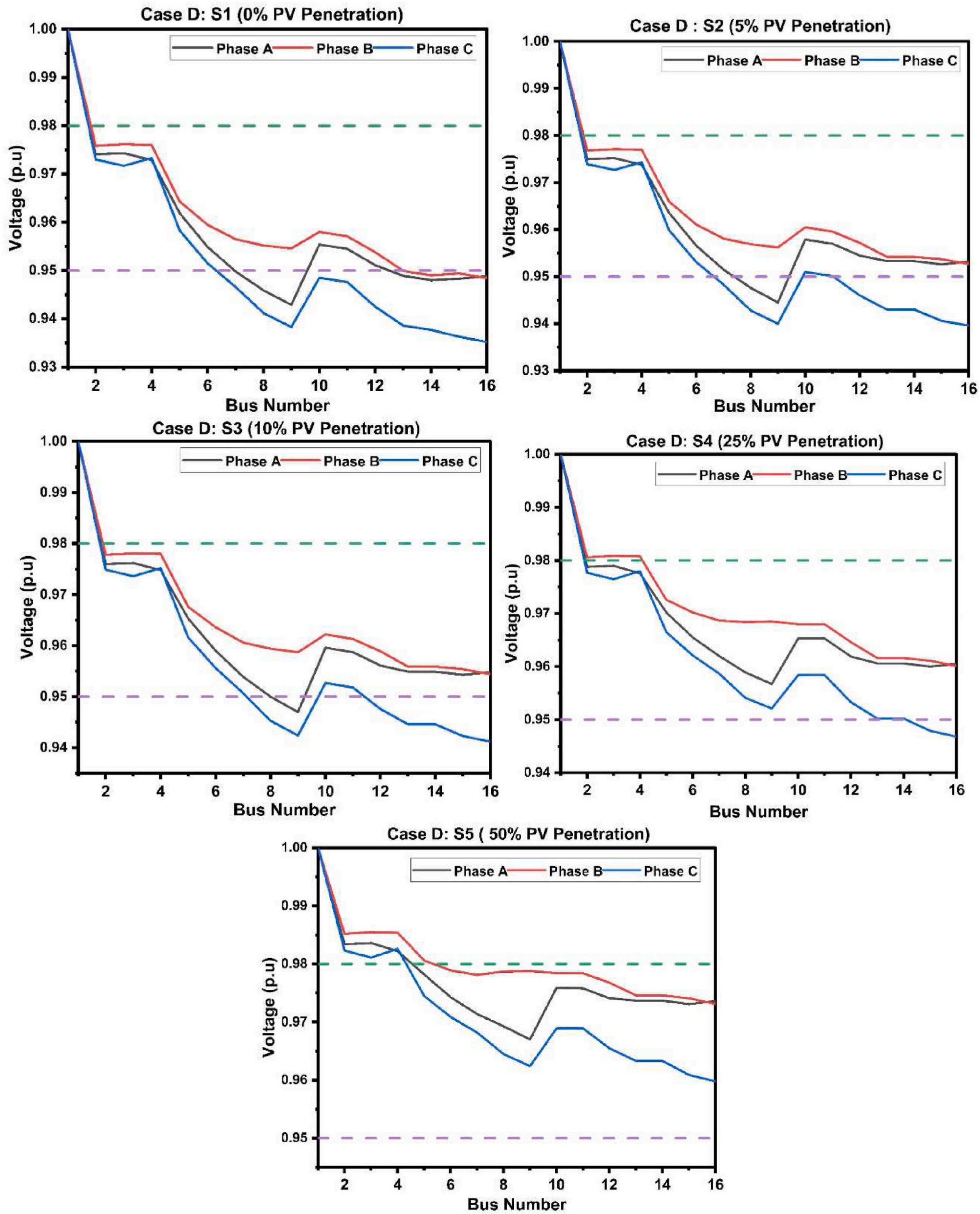


Fig. 8. Case D: System's per unit (p.u) voltage profile with five scenarios from 0 to 50% PV Penetration.

e. Case E: 2–4 kVA Load on Each House

example FiT. For the calculations, a solar PV system with a capacity of 4 kWp is considered.

4.1. Financial impact with current NEM policy

The power sector load is going to be reduced by single-phase NEM, resulting in a revenue shortfall. So, the IESCO's financial data was used to compute the revenue loss. IESCO has a relatively high recovery rate when compared to other distribution companies in Pakistan. It serves 2.7 million domestic users, with 96% of connections being single-phase. In this case, the 4 kWp solar PV was assumed per house for the calculation of revenue loss.

The present NEM FiT for single-phase is the same as the three-phase prosumers. The existing policy outlines the FiT at 9.6 cents/kWh during off-peak hours. Table 5 shows the financial impact of single-phase NEM consumers on the power sector, specifically the IESCO.

For a 4 kWp system, the assumptions taken are as follows:

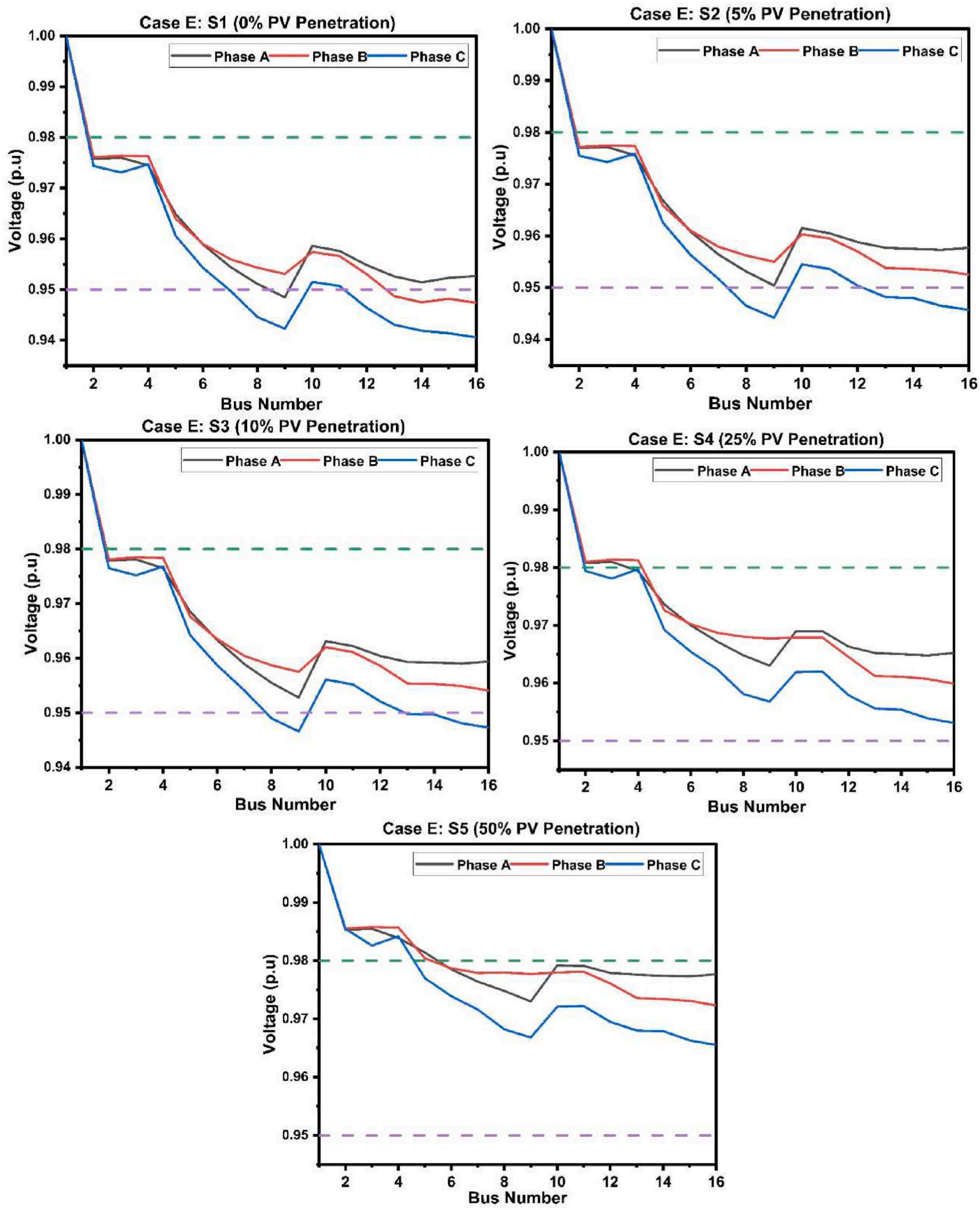


Fig. 9. Case E: System's per unit (p.u) voltage profile with five scenarios from 0 to 50% PV Penetration.

- Each single-phase house consumes 400 kWh/month
- Each single-phase house has a sanctioned load of 4 kW

Form Table 5, the IESCO will have 529.4 MW of distributed generation capacity if 5% of its customers have installed solar PV. In this case, the number of units generated by solar PV would be around 0.785 TWh per year. The expected revenue gain is $ 0.28 million. Similarly, a 10% gain in solar PV revenue will result in a revenue gain of around $ 0.57 million in the residential sector. As the PV penetration increases the net benefit increases. In addition, the solar PV-generated units will reduce reliance on fossil-fuelled power plants. As a result of green energy, overall emissions are reduced.

4.2. Financial impact of single-phase NEM policy with example feed-in tariff

The three-phase consumers do not receive a subsidized electricity. So, the NEM FiT for a three-phase prosumers during off-peak hours is 9.6 cents/kWh. This is excessively exorbitant for a single-phase consumers who already receives subsidized electricity. According to the new DISCO

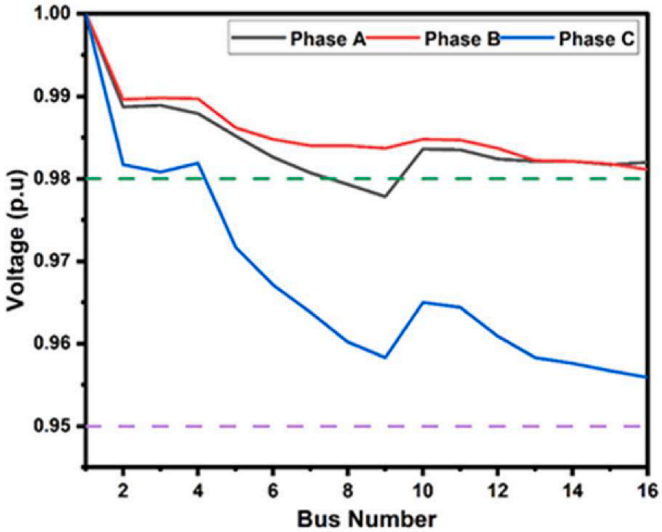


Fig. 10. The per unit (pu) voltage profile for unequal solar installed among the three-phases.

laws, the appropriate tariff slabs provide a significant amount of subsidies to the single-phase consumer, as shown in Fig. 14. The NEM feed-in tariffs, generally available to single-phase NEM customers, are the same as those offered to three-phase customers. The feed-in tariff structure should be revised as single-phase users can have NEM through single-phase inverters on a single-phase connection rather than switching to a three-phase connection. Such an example tariff could assist DISCOs to gain some money while reducing the financial loss stated in the preceding section. The net benefit has been calculated for assuming each single-phase consumer installs a 4 kWp solar system, assuming.

- Each single-phase house consumes 400 kWh per month
- Each single-phase house has a sanctioned load of 4 kW

Table 6 shows the full summary of PV penetration and associated related revenue benefits. IESCO will have 529.4 MW of distributed generation with 5% solar PV. Solar PV would generate roughly 0.785 TWh per year in this scenario. The power sector is expected to get a net benefit of $ 7.79 million from IESCO. Similarly, 10% solar PV penetration will result in a revenue gain of $ 15.58 million in the home sector. Furthermore, with 25% and 50% solar PV penetration, the net benefit will be around $ 38.96 million and $ 77.92 million, respectively. So, from the calculation, the option 2 is suitable for the DISCOs to get more benefit.

5. Conclusion and policy implications

5.1. Recommendation and policy interventions for enabling single-phase Net Energy Metering

The following recommendations should be addressed to make single-phase NEM successful in Pakistan and other developing nations, based on best practices, research literature, interviews with DISCO staff, and the techno-economic evaluation conducted earlier in the study.

5.1.1. Requirement of technical studies

Research should be done to make single-phase NEM successful without affecting grid technical operations. These studies are related to the NEM placement site and feeder and DT level studies to ensure that NEM operates appropriately. Before adopting single-phase NEM, standards, and specifications for components including inverters, power control units, conductors, lightning arrestors, energy meters, and data acquisition systems should be determined based on current worldwide standard practices. More importantly, components must comply with all applicable laws and regulations. As the number of single-phase NEM users grows, standard-compliant components and technical studies will ensure that the grid operates safely and reliably.

Table 3
Power Loss of cable, transformer, and total system loss in active KW, reactive kVar and apparent KVA for all the cases and scenarios.

Power Loss										
		Cable Loss			Transformer Loss			Total Loss		
Cases	**Scenarios**	**Active Power (kW)**	**Reactive Power (kVar)**	**Apparent Power (kVA)**	**Active Power (kW)**	**Reactive Power (kVar)**	**Apparent Power (kVA)**	**Active Power (kW)**	**Reactive Power (kVar)**	**Apparent Power (kVA)**
Case A	**S1 (0%)**	0	0	0.00	0.3	1	1.04	0.3	1	1.04
	S2 (5%)	0	0	0.00	0.3	1	1.04	0.3	1	1.04
	S3 (10%)	0	0.1	0.10	0.3	0.9	0.95	0.3	1	1.04
	S4 (25%)	0	0.1	0.00	0.3	1	1.04	0.3	1	1.04
	S5 (50%)	0.3	0.1	0.32	0.4	1.2	1.26	0.7	1.3	1.48
Case B	**S1 (0%)**	0.4	0.1	0.41	0.6	1.5	1.62	1	1.6	1.89
	S2 (5%)	0.4	0.1	0.41	0.5	1.4	1.49	0.9	1.5	1.75
	S3 (10%)	0.4	0.1	0.41	0.5	1.4	1.49	0.9	1.5	1.75
	S4 (25%)	0.3	0	0.30	0.4	1.3	1.36	0.7	1.3	1.48
	S5 (50%)	0.1	0	0.10	0.4	1.1	1.17	0.5	1.1	1.21
Case C	**S1 (0%)**	1.7	0.4	1.75	1.6	3	3.4	3.3	3.4	4.74
	S2 (5%)	1.4	0.4	1.46	1.5	2.8	3.18	2.9	3.2	4.32
	S3 (10%)	1.4	0.4	1.46	1.3	2.5	2.82	2.7	2.9	3.96
	S4 (25%)	0.9	0.2	0.92	1.1	2.2	2.46	2	2.4	3.12
	S5 (50%)	0.4	0.1	0.41	0.7	1.6	1.75	1.1	1.7	2.02
Case D	**S1 (0%)**	3.6	1	3.74	3.1	5.3	6.14	6.7	6.3	9.20
	S2 (5%)	3.2	0.8	3.30	2.8	4.9	5.64	6	5.7	8.28
	S3 (10%)	2.9	0.6	2.96	2.6	4.6	5.28	5.5	5.2	7.57
	S4 (25%)	1.9	0.6	1.99	2	3.4	3.94	3.9	4	5.59
	S5(50%)	1	0.3	1.04	1.1	2.2	2.46	2.1	2.5	3.26
Case E	**S1 (0%)**	3.2	0.9	3.32	2.9	4.9	5.69	6.1	5.8	8.42
	S2 (5%)	2.7	0.8	2.82	2.6	4.4	5.11	5.3	5.2	7.42
	S3 (10%)	2.4	0.6	2.47	2.4	4.1	4.75	4.8	4.7	6.72
	S4 (25%)	1.6	0.3	1.63	1.7	3.2	3.62	3.3	3.5	4.81
	S5 (50%)	0.8	0.2	0.82	0.9	2	2.19	1.7	2.2	2.78

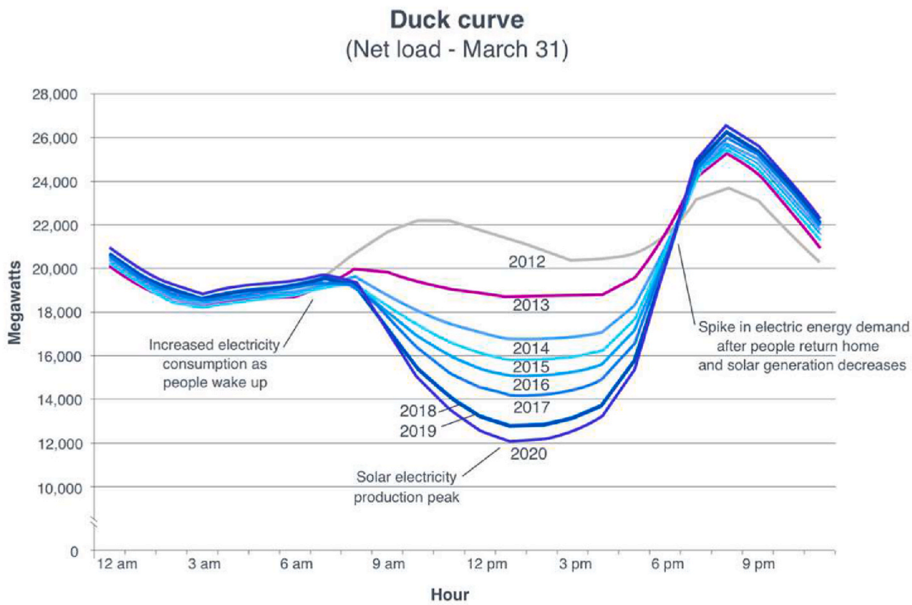


Fig. 11. Solar PV impact on the load curve (California) (Hou et al., 2019).

Table 4
Estimation of Single-phase NEM connection in IESCO.

IESCO Stats (millions)		Solar Capacity		
Total Domestic Connections	**2.77**	**4 kW per house**	**MW Installed**	**Annual Generated Units (TWh)**
Single-Phase Connections	**2.65**			
5% Single-Phase Consumers	0.13	529,400	529.4	0.784
10% Single-Phase Consumers	0.26	1,058,800	1058.8	1.569
25% Single-Phase Consumers	0.66	2,647,000	2647	3.923
50% Single-Phase Consumers	1.32	5,294,000	5294	7.846

5.1.1.1. Pre and post-installation survey. For single-phase NEM, a pre- and post-installation survey is required. Periodic checks should also be performed at regular intervals. Checks such as space and bill evaluation should be included in pre-installation surveys. Inverter requirements, earthing standards, conductors, energy meters, and lightning arrestors should be checked during the post-installation assessment. The current NEM requirements include pre- and post-installation surveys, which should be carried out in single-phase NEM. On the other hand, periodic visits are not covered by the present NEM laws. Therefore, DISCOs cannot know if customers modify their configuration or even add extra solar power. Similarly, if a solar PV update is carried out for components that need to be replaced regularly, the consumer may jeopardize safety measures. Therefore, the DISCOs will be able to keep the NEM in compliance with regulations through monthly visits.

5.1.1.2. Ensuring power balance. Single-phase NEM, unlike three-phase NEM, can result in voltage imbalances. If one phase has more solar PV than the others, unbalancing should create power quality challenges. So, solar PVs must be distributed fairly among the three phases. DISCOs are bound by the distribution code's upper restrictions on imbalances. Solar PV should be divided into all phases equally to prevent breaking the permitted imbalance ratio.

Load flow studies should be undertaken at DTs level if the number of NEM exceeds a particular limit. DISCOs will be able to establish a limit on NEM connections based on network capacity due to these investigations. This will also help DISCOs to encourage NEMs in locations where voltage regulation is problematic due to great distances from DTs. Therefore, DISCOs may provide some incentives to prosumers for building NEM connections.

5.1.1.3. Use of ICT tools. Without the use of proper ICT tools, considerable penetration of single-phase NEM is not achievable. DISCOs will benefit from the ICT tools in a variety of ways. A smart meter, for example, may give DISCOs a mechanism to communicate with and monitor NEM sites.

Only ICT tools can allow for high-granularity data collecting from NEM sites. For better optimization and planning at DISCOs, this data includes NEM's load and generation profiles. Furthermore, the data can assist DISCOs in developing new NEM rate models, resulting in a win-win situation for both DISCOs and consumers. The information will also aid DISCOs in load forecasting, allowing them to efficiently manage dispatch and unit commitment for their generation contracts. DISCOs can also change power factors by modifying the NEM site's reactive power.

Furthermore, ICT technologies may improve maintenance by predicting faults and reducing the time to resolve complaints. NEM can also cause a generation imbalance; hence it should be limited in emergencies. DISCOs would disconnect NEMs in a crisis using ICT tools, ensuring the grid's reliability and safety.

5.1.2. Enhanced business models

5.1.2.1. Capital expenditure model (CAPEX). In Pakistan, the NEM business model is still in its infancy. The CAPEX model, which is a consumer-oriented model, is currently being used. The consumer fully invests in the NEM in this arrangement. However, this strategy is only helpful for individuals who have a substantial amount of money to invest. Therefore, this approach can severely suppress NEM's growth.

5.1.2.2. Renewable energy service company (RESCO). To get the most out of NEM, Pakistan must implement a more user-friendly business model, such as the RESCO model, which gathers momentum in Pakistan but is still not widely used. RESCO is the third-party investor who provides the following categories to enable NEM at the client's location:

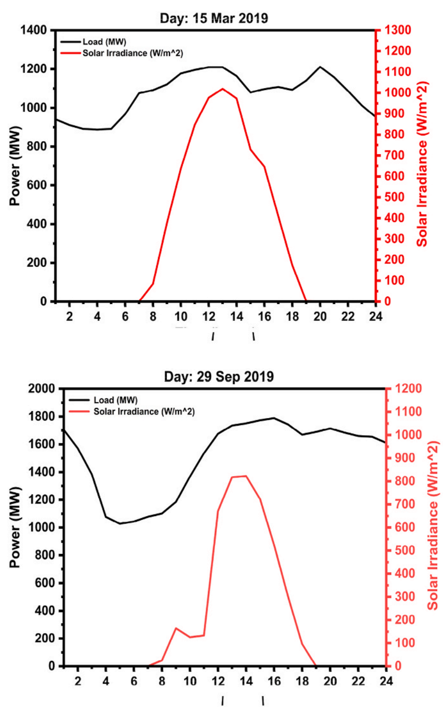


Fig. 12. Load curve along with solar irradiance (W/m2).

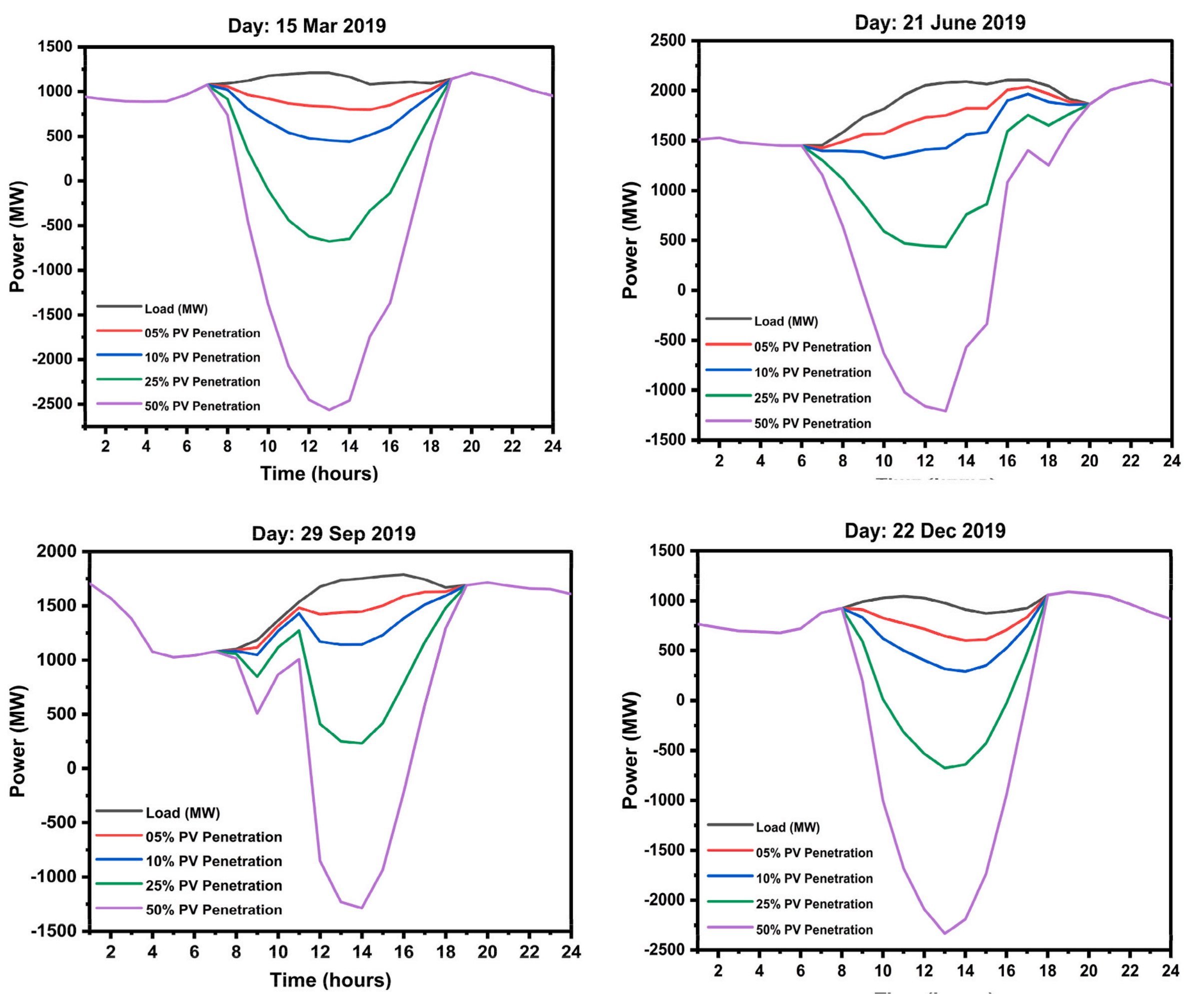


Fig. 13. Duck curve impact on the IESCO network.

Table 5
Calculations of revenue in the power sector using “Option 1″ for a 4 kW solar system installed.

IESCO Stats. (Connections in millions)		Solar Capacity		Self-Consumption (TWh)	Number of Feed-In Units (TWh)	Power Sector Revenue ($ Million)		
Total Single Phase	2.6	Total MW Installed	Generated Units (TWh)			Current Govt. Subsidy*	DISCO Payment to Prosumers with Option 1	Net Benefitwith Option 1
5% Single Phase	0.13	529.4	0.785	0.635	0.149	**14.56**	**14.27**	**0.28**
10% Single Phase	0.26	1,058.8	1.569	1.270	0.299	**29.11**	**28.55**	**0.57**
25% Single Phase	0.66	2,647	3.923	3.176	0.747	**72.79**	**71.37**	**1.41**
50% Single Phase	1.32	5,294	7.846	6.353	1.493	**145.57**	**142.74**	**2.83**

SCHEDULE OF ELECTRICITY TARIFF W.E.F 12-02-2021

A1 General Supply Tariff-Residential

Sr. No.	Tariff Category/Particulars	Fixed Charges Rs/KW/M	Uniform Tariff Variable Charges (Rs/KWh)		Applicable Variable Charges	
a)	For Sanctioned load less than 5 kW					
i	Up to 50 Units	-		4		3.95
	For Consumption exceeding 50 Units				-	-
ii	For first 100 Units	-		14.89		7.74
iii	a.101-200 Units			16.41		10.06
iii	b.201-300 Units	-		17.53		12.15
iv	301-700 Units	-		19.07		19.55
v	Above 700 Units	-		20.61		22.65
b)	For Sanctioned load 5 kW & above					
			Peak	Off-Peak	Peak	Off-Peak
	Time of Use	-	20.27	13.1	22.65	16.33
As per Authority's decision residential consomer will be given the benefits of only one previous slab						

Fig. 14. Slab based tariff for a single-phase consumer.

Table 6
Calculations of revenue in the power sector using “Option 2″ for a 4 kW solar system installed.

IESCO Stats. (Connections in millions)		Solar Capacity		Self-Consumption (TWh)	Number of Feed-In Units (TWh)	Power Sector Revenue ($ millions)		
Total Single-Phase	2.64	Total MW Installed	Generated Units (TWh)			Current Govt. Subsidy	DISCO Payment to Prosumers with Option 2	Net Benefit with Option 2
5% Single Phase	0.13	529.4	0.785	0.635	0.149	**14.56**	**6.77**	**7.79**
10% Single Phase	0.26	1,058.8	1.569	1.270	0.299	**29.11**	**13.53**	**15.58**
25% Single Phase	0.66	2,647	3.923	3.176	0.747	**72.79**	**33.83**	**38.96**
50% Single Phase	1.32	5,294	7.846	6.353	1.493	**145.57**	**67.66**	**77.92**

1. RESCO Power Purchase Agreement
2. Guaranteed Savings Contract
3. Shared Savings Contract
4. Roof Rent Agreements

New business models such as utility anchored and community anchored must be encouraged for the adoption of solar rooftop systems.

5.1.2.3. Utility anchored. Utility-anchored business models can help to mitigate risks, improve system cost-performance, and scale NEM technology. Utility-anchored business models can also be combined with RESCO or customer-anchored business models to enhance the benefits for both the consumer and the utility. Demand aggregation, On-bill finance, and payment assurance are all used in Utility Anchored Models.

5.1.2.4. Community anchored. The community-anchored concept refers to several community members sharing local solar facilities and receiving credit on their electricity bills for their portion of the power produced. This strategy allows people to combine their roof space, investment, and usage to form a solar demand and supply cooperative. This is currently the most popular solar PV model in the United States. Pakistan can also get benefit from using this business model.

5.1.2.5. Customer awareness and marketing. DISCOS should launch a prosumer awareness campaign in their area, stressing the benefits and advantages of their product. A structure for grading and impaneling developers could help to speed the uptake of solar rooftop systems by giving consumers a choice among reputable solar developers and ensuring quality. It would help boost consumer confidence and provide DISCOs with additional assurances about the quality of solar rooftop systems connected to their distribution network.

5.1.3. Policy recommendations to address regulatory and technical challenges

5.1.3.1. New regulations to enable single-phase Net Energy Metering. Pakistan's NEM policy is appropriate for three-phase NEM. However, some new policies are required to ensure that single-phase NEM is operated safely. The amount of power exported from NEM should be restricted. A high number of single-phase NEM can cause power imbalances. As a result, solar export limiters should be used to cap energy export from NEMs. Solar export limiting is a technique used for limiting PV generation. Solar export limits have been steadily implemented in all benchmark states with increasing PV penetration on their aging networks for years, stating that it is required to avoid voltage stability difficulties in regions with considerable rooftop PV penetration. The local electrical network operator defines the grid export limit of a rooftop solar system – sometimes on a case-by-case basis, sometimes according to an industry standard, and usually around 5 kW. However, as more solar is installed on systems constructed and configured to distribute electricity just one-way, solar export limits are tightening. Solar export limiting is accomplished using a device known as a Solar export limiter, which can also be found in to newer intelligent inverters. Solar export limiters are essential for Pakistan's successful implementation of single-phase net metering, as they prevent phase unbalancing and limit reverse power flow. The solar export limitation is a built-in function on most modern inverters. A fixed limit may be required at first, but the cap can be changed based on grid requirements as the network gets more modern and reliable.

5.1.3.2. Duck curve mitigation techniques. Pakistan, unlike many other countries, has fewer industrial loads. This explains why the duck curve had quite an impact in the IESCO scenario. The duck curve makes dispatch and planning challenges. The literature discusses a variety of mitigation techniques for flattening the duck curve's belly. DISCOs in Pakistan, on the other hand, have constraints when it comes to implementing current duck curve mitigation strategies. The following are some of the strategies DISCOs can use to mitigate the impact of the duck curve.

a) Smart Meter and Variable tariff

Variable pricing is one approach for reducing the load curve's impact. However, any sort of variable pricing involves smart metering that monitors the load at regular intervals. Customers and DISCOs can communicate efficiently through smart meters to transmit pricing signals. Customers can most effectively increase and decrease their load by using price signals. Different price signals may be designed depending on the home and industrial consumers. DISCOs may require smart installation with NEM to assist in regulating the duck curve. DISCOs, on the other hand, should be equipped with information technology tools to deliver price-based signals and additional load and generation curtailment actions.

b) Daytime Load Growth and Load Management

Shifting flexible loads to daytime hours is another way to decrease the impact of the duck curve. Some flexible loads, including water pumps, tube wells, and industrial processes, should only run during daylight hours to flatten the duck curve belly. Furthermore, some other energy sectors that generally use natural gas, such as cooking, water, and space heating, may switch to grid power. Pakistan is experiencing a severe natural gas crisis, and switching gas-based loads to electricity could help relieve some of the pressure on the country's natural gas resources.

c) Grid to Vehicle Charging

In Pakistan, electric cars (EVs) are being introduced. The charging of electric vehicles will necessitate a substantial amount of electricity from the grid. EVs are flexible loads that can be charged during the day. So, EV rates for various charging levels of EVs may be provided to encourage charging during the day. This type of tariff will be advantageous in places like offices where EVs are parked for long periods.

d) Energy Storage Systems

The installation of large-scale batteries can also help to reduce the duck curve. These batteries store solar energy throughout the day and use it at night to minimize the utility's ramp rate demand. However, due to the high cost of the batteries, the storage capacity has yet to be successfully applied on a residential scale. To provide reliable capacity during multi-day and multi-week periods of low renewable energy output, storage must have a fleet wide lifetime of 100–1000 h. Current storage technologies, such as lithium-ion, cannot provide this kind of performance on a cost-effective basis, and most only have capacities of 1–10 h.

e) Shifting to Direct Low Current-Voltage (DC residential buildings)

Direct Current (DC) distribution rather than Alternating Current (AC) distribution can reduce overall distribution system losses. Customers may be encouraged to use intelligent DC loads, such as DC air conditioners, DC motors, and DC-based freezers. Due to the absence of inrush current required by AC loads, these DC loads will not strain the grid during peak hours. A DC home with a modern DC load can mitigate the duck curve if combined with intelligent meters.

6. Conclusion

Rooftop solar systems are expected to become more common and affordable in the future. It's worth noting that, unlike thermal power facilities, NEM (single or three-phase) is dominated by onsite generating owned by customers. As a result, public acceptance and engagement are critical to its success. Manufacturing capacity, R&D investment, an investor-friendly atmosphere, talent development, low-voltage grid connectivity of variable solar resources, and regulatory decisions are all key national challenges that must be addressed.

Voltage fluctuations may arise when solar PV penetration increases in LV single-phase distribution networks due to voltage imbalances induced by the solar PV system into the network. This is especially critical in homes with single-phase connections. When domestic net-metered solar PV numbers rise, it's critical to look into single-phase PV power feed-in levels before voltage unbalances exceed standard limits. The ETAP simulator was used to model various degrees of PV penetration on the single-phase in this study, which used an IESCO reference feeder network. According to the technical analysis, increasing single-phase net-metered connections can improve voltage regulation and reduce line losses.

Furthermore, because most of Pakistan's distribution companies' feeders are overburdened, a rise in PV penetration relieves these overloading conditions and increases the voltage level within distribution regulation limits. Moreover, If correct mitigation strategies are used, the enhanced duck curve effect can be minimized. IESCO's revenue will increase as solar PV penetration rises from 0 to 50% from an economic standpoint. As shown in the (financial impact) results, further revenue gain opportunities can be achieved with the proper design and implementation of the improved proposed tariff.

In conclusion, Pakistan's transmission infrastructure can barely handle the predicted load in the upcoming years. And the losses on both the transmission and distribution networks are significant, resulting in waste and chronic revenue deficits at the DISCOs. In reality, the distribution system constraints represent an opportunity for NEM to alleviate some of the system's issues by reducing distribution losses, reducing network congestion, and supplying additional power to eliminate or minimize load-shedding. NEM, when strategically deployed, can also help with voltage regulation on the distribution network, particularly in areas where feeders are overburdened. It can also improve the economic structure of Pakistan's national electrical power regulatory authority by improving its revenue gain. Last but not least, NEM can serve as the primary instrument in attaining the NDC target of Pakistan to shift to 60% renewables in the energy mix by 2030 by promoting rooftop solar PV.

Solar systems distributors and electricity distribution companies have also been given tips and guidance based on carefully plotted findings to enable the orderly and sustained development of Pakistan's single-phase, net-metered DG markets.

CRediT authorship contribution statement

Muhammad Usman Tahir: Conceptualization, Methodology, Data curation. **Kiran Siraj:** Data curation, Formal analysis, Writing – original draft. **Syed Faizan Ali Shah:** Validation, Writing – review & editing. **Naveed Arshad:** Visualization, Investigation, Supervision.

Declaration of competing interest

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

Data availability

The authors do not have permission to share data.

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