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Techno-economic Assessment of Single-Phase Net-Metering

Study Report
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Techno-economic Assessment of Single-Phase Net-Metering

Renewable Energy and Energy Efficiency II - Pakistan

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Executive Summary

Net Energy Metering or Net Metering[1] is a promising mechanism of electricity billing that allows consumers to generate electricity, usually through renewable energy resources, and feed the excess power to their local power grid. The consumers get credit for the units fed into the grid. Net Energy Metering (NEM) provides a cheaper, greener, and decentralized approach to add new energy generation to the grid. Onsite generation offers many technical advantages to the grid, such as fewer power losses due to shorter transmission distance and reduced peak generation requirement for the grid. The latter is possible if the solar photovoltaic's peak coincides with the grid's peak load. Further, onsite generation with battery storage may provide resilience against grid breakdowns. Additionally, the NEM facility does not require utility companies to invest in a generation system as the building owner bears most solar PV installation costs.

Single-Phase Net Energy Metering in Pakistan and Around the World

At present, the regulations in Pakistan allow NEM connections on three-phase connections only. As of mid-2021, the three-phase NEM market in Pakistan has an installed capacity of 202 MW. The current NEM policy of Pakistan does not delineate regulations to install NEMs on single-phase connections directly using single-phase inverters. Single-phase electricity connections may also get a NEM facility if they first convert to NEM enabled three-phase connection. A typical single-phase connection has between 2-4 kW sanctioned load, and Pakistan's maximum allowed NEM capacity is one and a half times the sanctioned load.

Many countries around the world allow single-phase NEM. The maximum capacity of single-phase NEM varies from as low as 3.6 kW in Malta to as high as 10 kW in Japan, but most countries generally allow up to 5 kW capacity. Some countries allow larger capacities if a solar export limiter is installed. A solar export limiter restricts the feed-in beyond the maximum permitted capacity.

Pakistan's total domestic electricity connections stand at around 28.25 million. More than 90% of all connections in the domestic sector are single-phase. If regulation allows direct NEM facility on single-phase connections, the NEM market is expected to grow significantly.

Technical Challenges and Impact of Single-Phase Net-metering

Single-phase NEM and three-phase NEM share many challenges, such as generation unpredictability, power quality, and voltage regulation. However, Single-phase NEM, in particular, have one major additional challenge in that they may cause phase imbalances if the connections are not equally divided between different phases. Accounting for this constraint, many countries enforce solar export limiters to keep phases balanced.

Impact of Distributed Generation on Load Curve

For the case study scenario, Islamabad Electric Supply Company (IESCO) was selected, which has 96% single-phase residential connections. The study revealed that Distributed Generation from single-phase NEM impacts the load curve of the distribution company. Using single-phase NEM penetrations of 5%, 10%, 25%, and 50%, we model the impact on load curves of IESCO. IESCO's load curve in December touches a peak of 1087 MW, and with 5% NEM penetration, solar PV may contribute as much as 331 MW. Similarly, the load curve in June touches a peak of 2108 MW, and with a 5% NEM penetration, the solar PV peak touches 329 MW. Solar PV generates around 10.6% of the total units required to meet the IESCO load requirement for December, and for June, solar PV generates 19.28% of load requirements with 5% single-phase NEM. The impact of 5% and 10% of

[1] 'Net Energy Metering' and 'Net Metering' are used interchangeably in literature and are synonymous.

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 to note 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. Not only are enough generation resources required, but generation resources with a high ramp rate will be required to meet the rapid surge in the load curve. With 5% PV penetration, the ramp rate required is 0.89 MW/min, whereas the ramp rate required with 50% PV penetration the ramp rate is 9.54 MW/min.

Impact on Voltage Regulation and Power Losses

Onsite generation using NEM improves voltage regulation. Electricity connections far away from the substation experience voltage dips. This also results in power losses for the utility. However, onsite generation using solar PV solves both issues. Voltage improvement is directly proportional to the number of NEM connections. As most connections are single-phase, thus single-phase NEM allows better voltage regulation. In general, power losses reduce with an increase in NEM installations, except for the low load time of the year, usually the later part of the year.

Financial Impact

Solar PV allows onsite generation, consequently, reduces dependence on the grid. With each onsite generated unit, whether consumed locally or exported back to the grid, the utility company may face a revenue loss or gain, depending on the solar capacity installed and the feed-in tariff model. For example, with 5% solar PV penetration, the electricity sector may lose PKR 0.96 billion or gain PKR 1.79 billion in annual revenue from IESCO. However, this will also lower the country's oil import bill as presently 60% of electricity generation in Pakistan is from thermal sources with a significant share of imported fossil fuels.

Solar PV is a reality, and DISCOs cannot fight or flight this upcoming tsunami. However, DISCOs may convert this perceived challenge to an opportunity with the right strategy, regulations, financial and business models, and appropriate technical systems and know-how.

Recommendations

1. Single-phase NEM must require a pre- and post-installation inspection to ensure compliance with regulations. Periodic visits must take place for safe operations of NEM. Load flow studies should periodically be carried out in areas with high penetration of solar PV.
2. To minimize the risk of over-generation and voltage imbalances, a solar export limiter may be installed. Remote disconnection should also be available with utilities to avoid any damage to the grid.
3. With an increase in single-phase NEM connections, DISCOs must balance the solar PV on each phase. Thus, with each new single-phase NEM connection, a phase balancing exercise must take place.
4. Modern inverters have a built-in feature of a solar export limiter. A fixed limit may be required at the start, but as the network becomes modern and robust, the cap can be adjusted based on the grid requirements. Therefore, the solar export limiter is the key to a successful implementation of NEM while keeping the grid's phase imbalance under check.
5. Monitoring and management of a large number of NEM connections are not possible manually. Therefore, appropriate ICT tools to manage connections and maintain safe operations are prerequisites for large NEMs. Smart metering coupled with the time-of-use tariff is desired to keep the solar PV generation and load under control with the right price signals between DISCOs and consumers.

6. Under-voltage feeders should be prioritized for NEM to reap the benefits of improved voltage regulation and reduced power losses.
7. New business models to accommodate NEM must create a win-win situation for both customers and utility companies. This also includes tariff redesign for feed-in electricity at rates that are profitable for both customers and DISCOs.

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List of Abbreviations

AC	Alternating Current
AEDB	Alternative Energy Development Board
APPC	Average Pooled Purchase Price
CAGR	Compound Annual Growth Rate
CCGT	Combined-Cycle Gas Turbine
CAPEX	Capital Expenditure Model
DERs	Distributed Energy Resources
DG	Distribution Generation
DISCOM	Distribution Company
DT	Distribution Transformer
DPV	Distributed Photovoltaic
DC	Direct Current
ETAP	Electrical Transient Analyzer Program
GW	Gigawatt
GWp	Gigawatt Peak
GHG	Green House Gas
IESCO	Islamabad Electric Supply Company
kW	Kilowatt (1000 W)
kWp	Kilowatt Peak
LV	Low Voltage
LESCO	Lahore Electric Supply Company
LCOE	Levelized Cost of Energy
MEPCO	Multan Electric Power Company
MW	Megawatt
MWp	Megawatt Peak
NEM	Net Energy Metering
NEPRA	National Electric Power Regulatory Authority
OCGT	Open-Cycle Gas Turbine
PV	Photovoltaic
Prosumers	Producer-Consumers
RESCO	Renewable Energy Service Company
Solar PV	Solar Photovoltaic
T&D	Transmission And Distribution

1. Introduction:

Today, the world faces a fossil fuel deficit, energy scarcity, and potentially dangerous consequences of rising levels of Green House Gas (GHG) emissions and fluctuating oil prices. Therefore, developing alternative energy supplies with high efficiency and reduced emissions is critical. Solar energy technologies are emerging as the leading contender for fulfilling energy needs. Solar photovoltaic (PV) systems use direct sunlight to generate electrical energy. Solar PV includes utility-scale solar PV, Agri-photovoltaics, floating solar PV, and rooftop solar PV.

Utility-scale solar PV is the dominant energy source at present, but by 2024 global distributed solar PV, which includes rooftop solar PV, is expected to double to 530 GW. This increase in distributed solar PV capacity will equal onshore wind capacity and will account for nearly half of the total solar PV worldwide. According to International Energy Agency (IEA) 2019[2], three-quarters of this growth will come from the commercial and industrial sectors, while one-fourth will come from the residential sector.

The residential solar market installation has seen a rapid expansion in recent years. Even during the pandemic, new solar installations continued, and in 2020 the world installed 138.2 GW. China has maintained its leadership position with more than 30.1 GW in 2019[3], totaling 138.5 GW in 2020. The United States came second with a solar installation growth rate of 43%, resulting in 19.2 GW of newly installed capacity in 2020. Vietnam installed 11.6 GW and emerged as the third leading state in solar installation worldwide. Japan maintained its fourth rank after adding 8.2 GW in 2020. In terms of total installed capacity, the countries mentioned earlier account for more than 70% of the world's newly added capacity[4] in 2020. Pakistan, being a developing country, has a slow growth regarding solar installation. The total solar PV capacity of Pakistan, including utility-scale solar installations, is 1.09 GW. India experienced a downfall of 56 % in solar PV installation and installed only 3.9 GW in 2020.

Moreover, by 2022 South Korea plans to install one million solar PV systems in Seoul. Similarly, Australia, Canada, the European Union, China, the United States (US), and Japan have highly conducive policies for residential solar PV distributed generation growth. Figure 1 shows the top five countries in terms of installed solar power capacity.

Various countries have adopted different business models to integrate the solar rooftop with the grid. The building consumes most of the electricity generated during peak hours, with the remainder being fed into the grid. During periods when there is insufficient power generation by the solar PV, electricity is drawn from the grid. Moreover, large loads are served by drawing power from the grid.[5]

The Residential Solar Energy Market will grow at a Compound Annual Growth Rate (CAGR) of greater than 10% over the next five years with the help of policies like NEM[6], and the levelized cost of energy (LCOE) is expected to fall by approximately 15% in the residential sectors[7].

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[2] IEA (2019), World Energy Outlook 2019, IEA, Paris (https://www.iea.org/reports/world-energy-outlook-2019)

[3] Trends in PV applications 2020 (https://iea-pvps.org/trends_reports/trends-in-pv-applications-2020/)

[4] REN-21 Full Report (https://www.ren21.net/wp-content/uploads/2019/05/gsr_2019_full_report_en.pdf)

[5] Solar Industry Research Data(https://www.seia.org/)

[6] PV Status Report 2019; JRC Science for Policy Report, European Commission

[7] Future Of Solar (https://irena.org/-/media/Files/IRENA/Agency/Publication/2019/Nov/IRENA_Future_of_Solar_PV_2019)

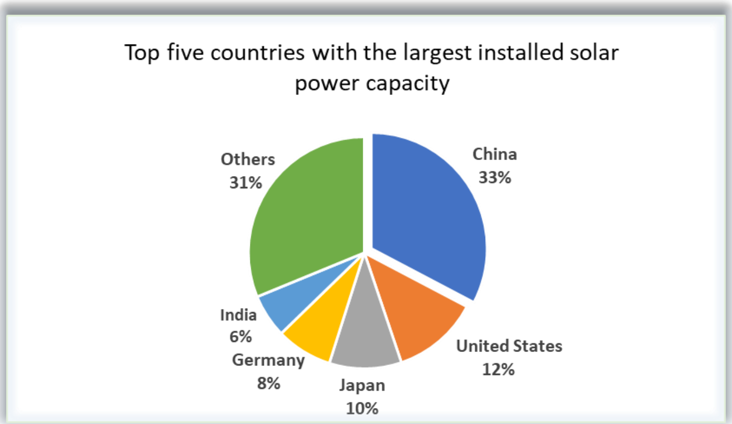


Figure 1. Top five countries with the largest installed solar power capacity

Net Energy Metering (NEM) is a billing and metering system that allows consumers to generate electricity and use it at a time other than when it is generated. This is accomplished by a crediting process that allows the customer to accumulate credit for electricity fed into the grid, which is then paid against the customer's grid-consumed power units. Consumers will become prosumers because of NEM, as shown in figure 2. NEM is typically offered with renewable energy systems (sometimes accompanied by energy storage). Because of its universality, solar PV is the most common source under NEM. Moreover, grid energy prices are frequently higher than generation costs with NEM, resulting in higher savings for consumers. When usage is low, such as when a resident prosumer goes on vacation, the system still makes money by feeding electricity into the grid.

Net Energy Metering (NEM) is a billing and metering system that allows consumers to generate electricity and use it later. NEM can be done for both single-phase and three-phase electrical supply.

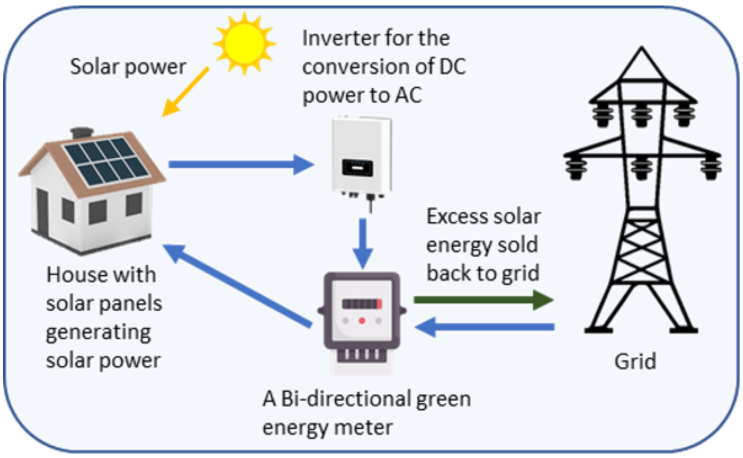


Figure 2. A net-metered enabled house

Advantages for Consumers:

NEM offers many advantages to the consumers, such as:

- Improved energy security due to resource addition.
- Self-sufficiency in generation due to onsite generation.
- Replacement for inefficiencies of UPS system, commonly used as a backup.

- Optimized local generation.
- Reduced cost vis a vis billing.
- Protection against inflation in energy prices.
- Reduction of carbon footprint.

Advantages for the Grid:

Few technical benefits that are associated with NEM include the following:

- Long-term investments in Transmission and Distribution (T&D) networks decrease since generation occurs behind the meter, close to consumption loads. Furthermore, when transmitting power from distributed generation instead of distant, large-scale generation plants, energy losses in the T&D network decrease.
- The network becomes more resilient because of the distributed nature of generation, and it can be operated with additional safety. Even if central generating units are unavailable or transmission networks are down, the network does not need to be fully shut down, especially if energy storage is available in the distribution network or with prosumers.
- If the renewable technology chosen for NEM generates electricity during peak hours, it saves utilities money on peak power acquisition and lowers total service costs.
- Single-phase NEM for low voltage direct current (LV DC) networks can also be evolved to enable efficient "grid additional functions" (voltage support, frequency support, black start, spinning reserve, and so on), with effective rules and energy storage.

1.1 Methodology and Study Assumption

The central objective of this study is to analyze the techno-economic impact of NEM in Pakistan for the single-phase consumers that account for more than 90% of the total residential connections. For the case study scenario, IESCO (Islamabad Electric Supply Company) was selected, where 96% of residential connections are single-phase connections. Four DISCOs were chosen for consultation: IESCO, LESCO (Lahore Electric Supply Company), GEPCO (Gujranwala Electric Power Company), and MEPCO (Multan Electrical Power Company). State-of-the-art policies of different countries in single-phase NEM were also studied. The data of a specific distribution transformer (DT) connected to a specific IESCO distribution feeder network was collected and simulated using Electrical Transient Analyzer Program (ETAP). The impact of a single-phase NEM on the daily load curve of the IESCO network was analyzed, and the report elaborates on techniques to mitigate the impact of the duck curve. Later, the financial impact has been observed and discussed in detail. Based on carefully plotted results, lessons learned from the leader states, interviews carried out with DISCOs' personnel, and software simulation, recommendations have been delineated.

1.1.1 Case Study Parameters

In comparison to other DISCOs, IESCO has a relatively high recovery rate of electricity bills. There are 5 circles, 19 divisions, and 109 sub-divisions in IESCO. The sanctioned load (MW) for each category in the IESCO network is shown in table 1. The overall number of residential customers on the IESCO network is 2.77 million, with single-phase customers accounting for 96 %. In this research, we have performed the simulation in ETAP using the following assumptions:

- The load's power factor is assumed to be 0.95.
- The maximum PV installation per house is the same as the sanctioned load at 1000 W/m^2 solar irradiance.
- The solar PV generation data was determined using the NREL PVWatts calculator for the Islamabad region.

- For the computation and economic evaluation of the duck curve, a solar PV installed capacity of 4 kWp per house was considered.
- The average unit (kWh) rate for IESCO residential sector was calculated using NEPRA's *State of the Industry Report.*

Table 1. Category-wise sanctioned load (MW) in IESCO network

	Domestic	Commer-cial	Industrial	Agricultural	Public Lighting	Bulk Supply	Others	Total
Category-wise sanc-tioned Load (MW)	4698.09	1250.58	1105.28	59.31	101.33	541.48	730.75	8486.82

2. Overview of Net Energy Metering

2.1 Single-Phase vs. Three-Phase Net Energy Metering

The world's first NEM connection was installed in 1979 in Massachusetts, United States. Since then, NEM has been successfully implemented in developed and many developing countries. NEM can be characterized into two types:

1. Single-Phase NEM

2. Three-Phase NEM

Single-phase supply is generally used in homes around the globe as home appliances generally do not require much electric power. Hence, a single-phase is sufficient to fulfill average household electric power demand. Around the world, NEM is enabled for both single and three-phase residential consumers.

There are two types of hybrid inverters:

1. Single-phase inverters
2. Three-phase inverters

A single-phase inverter could be connected in the following configurations

a. On a single phase of a house with a three-phase connection
b. On the house having a single-phase connection.

It is imperative to remember that a single-phase inverter can synchronize with any one of the phases in a three-phase grid. Small residential connections will usually not pose any problems under the 6-kW system. Before installing a single-phase inverter, it is ensured that the inverter is connected to the phase with the highest load. If the inverter is linked to the phase with the lowest load, phase imbalance will occur, affecting the grid's health[8].

In contrast, a three-phase inverter connects to all three phases and exports across all of them evenly. Logically, to install a three-phase inverter, the applicant must have a three-phase connection to the network. However, most residential connections worldwide are single-phase; therefore, single-phase inverters are the most common and are less costly than three-phase inverters.

The old architecture and infrastructure of the electrical power grid never intended for electrical power to flow in the opposite direction, and it was initially designed to be unidirectional. While this does not rule out the possibility of reverse power flow, it can be difficult for networks to handle technically when several DGs are all feeding back to the grid in the same region. This is the main reason why networks must put limits on solar system size, at least until the grid gets smarter and better at handling bidirectional electricity flow.

2.2 Single-Phase Net Energy Metering around the Globe

Single-phase NEM has been successfully implemented in many countries. Around the world, different distribution utilities have set the limit for the consumers, limiting the solar PV's maximum capacity. Countries following the best practices with high PV penetration in grids like Australia, the USA, and

[8] Partnership to Advance Clean Energy – Deployment (PACE-D) Technical Assistance Program Solar PV Rooftop Training Program - Handbook for Utility Engineers

India all have single-phase connections with a limit of 5 kW sanctioned load and a solar export limiter device. Following are the typical regulation of single-phase NEM:

- Most countries allow 5 kW solar PV capacity for single-phase NEM.
- Customers who intend to install larger than 5 kW on a single-phase supply must install a solar export limiting device (either built-in the inverter or additional devices) to ensure that excess output energy from the installed solar system should not export back beyond an allowed limit.
- DT capacity should not exceed 15% of its rated capacity, and after 30 kW solar PV capacity, a load flow study determines the DT load.

Australia, Belgium, California (USA), Netherlands, and Austria are predicted to be the top five markets for residential PV installations per capita in 2024. Close to home, India's total renewable energy target by 2022 is 175 GW, among which 40 GW is planned to be met through rooftop solar PV systems. This is planned to be achieved by the deployment of solar PV, mostly in single-phase residential connections.

Phase-balancing is an issue associated with the integration of distributed single-phase grid-connected solar rooftop PV systems. By applying proper power feed-in limitation implementation through advanced inverters having solar export limiters, the power feed-in limit by a single-phase user can be throttled at the limit set by the DISCOs of the respective country. In India, solar rooftop PV with a capacity of 5 to 10 kW can be connected in a single phase in some states, e.g., Karnataka and Madhya Pradesh. The power feed-in limitation of different countries is shown in table 2.

Table 2: Maximum allowed feed-in power for different countries.

Countries	Max Capacity That Can Be Installed (kW)	Max Capacity of Power Feed into the Grid (kW)
Countries With Higher Penetration of Rooftop Solar		
Australia	10	10, 5
Germany	4.6	100% Of the Install Capacity (4.6)
Italy	6	Less Than 6
Japan	10	<5
Countries with less than 10% penetration of rooftop solar		
Portugal and Bulgaria	5	<5*
Malta	3.6	< 4
Bangladesh	Not Available	Not Available
India	5	<3.5
		<4.5
Pakistan	1.5 times sanctioned load	Not Available
Spain	15	<5

Countries with single-phase NEM face issues with high penetration of solar PV. As distributed solar capacities increase, the single-phase system tends to move towards imbalances, which can further cause the following problems:

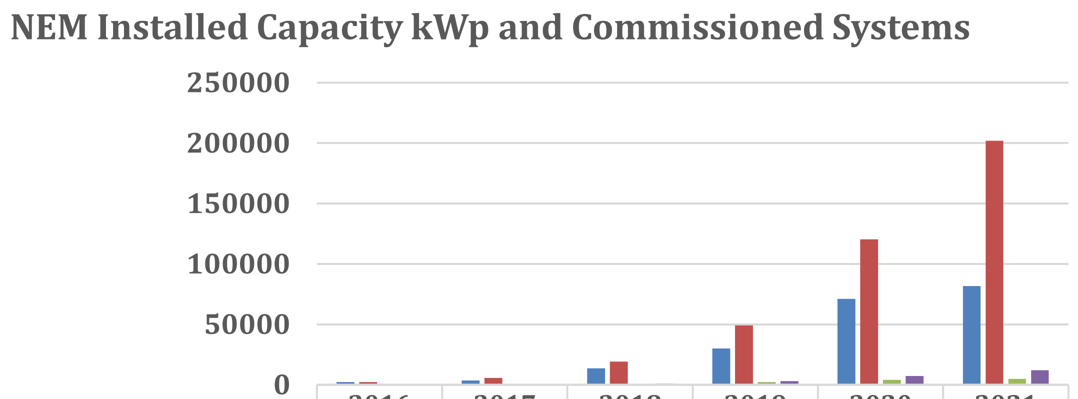
- In times of high RE generation, if more than the limited power is fed into the grid, then an over-voltage situation may occur.

- Low voltage distribution networks often exhibit uneven PV integration across phases due to the random connections of small single-phase rooftop PV generators in residential areas.
- Solar intermittency, e.g., due to cloud cover for a solar PV plant, may result in uneven power flow back to the grid, creating load flow issues.

Countries use a solar export limiter to solve some of the aforementioned problems. Solar export limiter limits the export of electricity back to the grid.

2.3 Single-Phase Net Energy Metering in Pakistan

Pakistan is supporting small-scale renewable energy through NEM for the past several years. Given the 30% renewable energy target by 2030, NEM may provide a cost-effective solution to meet the target. In 2015, NEPRA published the NEM rules and regulations under the "*Alternative & Renewable Energy Distributed Generation and Net-metering*", under which the government enacted net-metering. As a result, Pakistan's net-metered connections reached a total capacity of 202 MW by mid-2021, as shown in figure 3.



	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

Figure 3: Total Installed net-metered connection of Pakistan (June 30)

According to the *RE 2015 policy*, DISCOs must enter into a net-metering agreement with eligible end-users who are interested in implementing the RE system, subject to technical considerations. Pakistan's NEM policies only allow three-phase consumers to be connected to the grid via NEM. If a single-phase consumer wanted to apply for a NEM license, they have to first apply for a load extension and upgrade to a three-phase connection, after which their NEM application is considered. To rectify the problem faced by the single-phase consumers, NEPRA revised its policy in 2021,

Previously, if someone had a single-phase meter and would want to apply for the net-metering facility, they would first have to install a 3-phase meter. They would have to then wait for a bill, then based on that, they would apply for a green meter. This procedure could last 6-7 months and an additional cost.

making it more inclusive in favor of the single-phase consumers. According to the new policy, DISCOs are allowed to install a three-phase bi-directional meter directly to a single-phase connection upon request for load extension, as shown in figure 4.

The new policy by NEPRA has opened a massive opportunity for all the single-phase consumers. However, the single-phase consumer can still not connect directly to the national grid using a single-phase inverter.

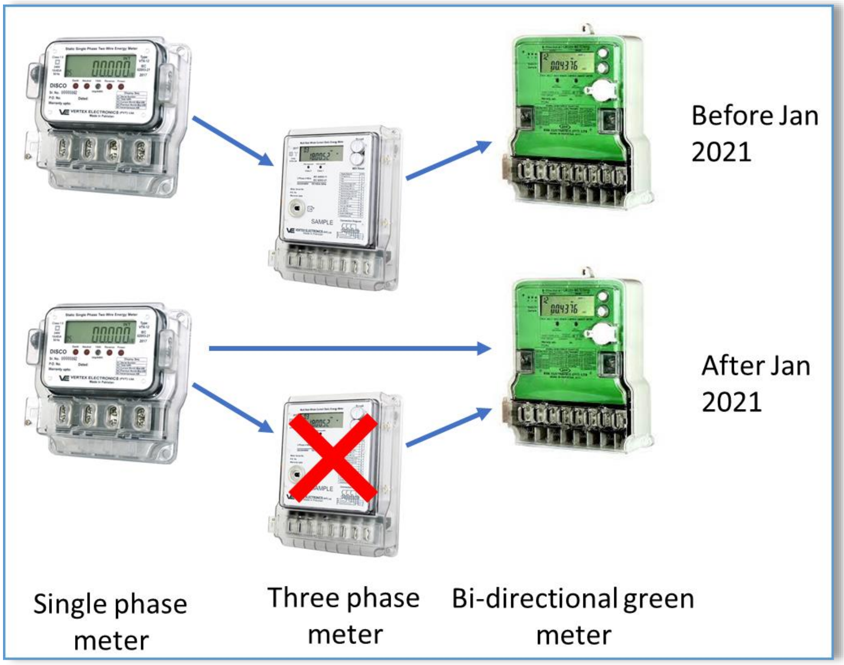


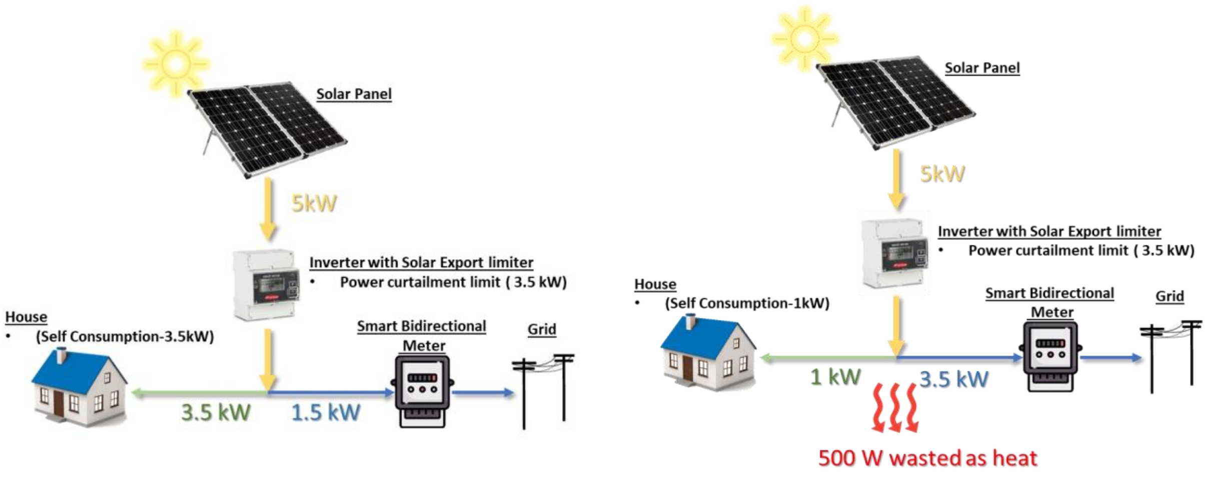
Figure 4. New policy for the single-phase user to get NEM through bidirectional meters

Right now, only Three-phase NEM is allowed in Pakistan. The consumers with single-phase connection are bound to increase their sanction load to 5 kW and get a three-phase bidirectional green meter.
NEPRA, 2015

With NEPRA's new NEM regulation, the eligible PV system capacities range from 1 kW to 1000 kW. But a consumer cannot install a solar PV capacity greater than 1.5 times of sanctioned load. The sanctioned load to a single-phase house is 1 kW to 4 kW, limiting the maximum PV capacity to 6 kW. However, to ensure that no more than 1.5 times is exported back to the system, the regulations require the provision of a solar export limiter.

The solar export limiter is the key to the successful implementation of single-phase NEM in Pakistan to avoid the phases' unbalancing and limit reverse power flow. Figure 5 shows the operation of the solar export limiter. If PV generates beyond the export limits set by the grid, the excess solar PV energy is curtailed by the solar export limiter.

Export limitation is defined by local energy network operator and entails employing additional hardware to throttle inverter power if solar export limitations, usually about 5kW, are exceeded.



(a) (b)

Figure 5: Solar export limiter with 3.5kW power feed-in limit.

2.4 Cost of Single and Three Phase Inverters and Smart Meters

Typically, the single-phase inverters are less costly than the three-phase inverters. A cost comparison of the most commonly used power inverters in Pakistan is given in table 3. Note that the prices have been quoted after consulting vendors. The quoted prices are off-the-shelf prices for broadband PLC smart meters.

Table 3: Price comparison of 5 kW single-phase and three-phase inverters.

Company	Prices (PKR)		
	5 kW Single Phase	5 kW Three Phase	Smart Meter
SMA	184,000.00	216,500.00	85,000.00
Fronius	195,000.00	216,500.00	50,000.00
SunGrow/Huawei	137,000.00	182,500.00	45,000.00
Solis/GoodWe	114,000.00	146,000.00	35,000.00
Nitrox	N/A	115,000.00	30,000.00

3. Technical Obstacles, Limitations, and Challenges

Being one of the first developing countries to adopt NEM, Pakistan has faced numerous challenges in deploying Net metered RE (solar and wind) systems. Electric utility companies' reluctance, low technical competence at various organizational levels of the utilities, lack of knowledge among stakeholders, and insufficient access to appropriate finance choices are among the primary impediments to the growth of single-phase NEM.

In order to enumerate and assess technical challenges, we looked at the single-phase NEM literature, studied countries where single-phase NEM is widespread, and finally interviewed technical personnel at fours DISCOs (IESCO, LESCO, GEPCO, and MEPCO). Three-phase and single-phase NEM have some common problems, while single-phase NEM has some specific challenges related to voltage imbalance.

3.1 Challenges Associated with Net Energy Metering

From a technological standpoint, significant levels of penetration of PV rooftop systems in electrical networks can impact grid stability. Following are some of the critical challenges of NEM single-phase or three-phase:

3.1.1 Generation Unpredictability

PV systems' exceptionally high penetration levels compared to the network's installed generation capacity may result in generation unpredictability. Photovoltaic systems are more unpredictable than classic DG systems such as diesel generators due to resource unpredictability.

3.1.2 Power Quality

Power quality is one of the main issues challenges faced by NEM. High penetration of NEM can generate power quality issues in the distribution network, such as voltage regulation and harmonic distortion contribution.

3.1.3 Voltage Regulation

Electrical networks must keep voltages below safe limits at all locations in the network to protect electricity users and their electrical equipment. The distribution networks set these constraints. With single-phase NEM enabled, two major types of voltages issues can arise.

a. **Voltage Rise:** The present LV distribution feeders will experience large-scale penetration of small rooftop photovoltaics because of the high number of single-phase consumers. Sometimes when the consumer’s consumption is lower than the power fed in, then these high levels of PV feed-in power may lead to reverse power flow. Due to which a sudden voltage rise will occur. These high voltages can further cause damage to consumer’s appliances. During peak load hours, however, in many developing countries, remote areas away from the DT suffer lower voltages than the rated voltages. PV Rooftop systems can thus be used to successfully provide voltage regulation in remote grid sites, particularly during the day.

b. **Voltage Fluctuations:** The intermittent nature of solar energy may lead to rapid voltage fluctuations that can impair the LV distribution feeder, and in some cases, may overheat the power lines. State-of-the-art inverters are available that can mitigate the issue of voltage fluctuation at consumer's end and keep it between safe limits. However, if the inverter, malfunctions then the voltage fluctuation problem can move outside the specified values. Remote monitoring and management software can also be used to give DISCO's the control for the remote disconnection of a problematic user if required.

3.1.4 Overloading of the Distribution Networks

Overloading of electrical network conductors and distribution feeders occurs when demand exceeds capacity in the electrical network or when higher levels of generation are supplied into the distribution network beyond the capacity of the conductors and feeders. If photovoltaic systems are distributed equally throughout the distribution network, network overload will not arise. However, if distributed PV (DPV) systems are clustered near the distribution feeder or in a specific area in the distribution network, the DT can be thermally overloaded. To keep it under check, different countries have set limits on PV System penetration. For instance, numerous states in India have set limits on PV system penetration as a %age of distribution feeder capacity ranging from 15% to 50%, with 30% being the most typical limit. The specifications of such limits are relatively safe because several factors determine thermal overload, the most important of which is demand rather than DPV systems. However, it may be noted that it will take a considerable amount of time before even such conservative limits as 30% of the feeder capacity are reached by DPV systems. Generally, the limit of 30% is working safely in countries like Europe and Australian states.

3.1.5 Phase Imbalance (single-phase)

Low-capacity solar power plants with single-phase inverters inject power into the grid through a single-phase injection point. This uneven power injection can cause phase imbalance. Simply injecting power to various phases in the same grid will correct this imbalance. Due to the limits defined by the utilities for the feed-in power injection, the general imbalance ratio among the three phases is defined to be 2%-3% for an unbalanced network. For example, a house connected to a phase might inject power more than the defined limit. This will cause higher currents to flow in the neutral phase and can affect the generation side. Different countries have different imbalance limitations. For example, Germany's limit is 4.6 kilowatts, while Australia's limit is 10 kilowatts in states where the grid is highly stable. India has a weak grid just like Pakistan; therefore, the limit of power injection back to the grid by a single-phase user is set between 3-4.5 kW[9]. Every utility/grid operator sets these restrictions periodically, based on its study of permitted imbalances. Before connecting a single-phase solar inverter to the grid, the developer must adhere to the utility company's phase imbalance limits. If Pakistan intends to reap the benefits of NEM, the problem of voltage imbalances (both due to excessive penetration above the established limitations and due to concentrated PV installation on a single-phase) between the phases of single-phase houses must be addressed.

[9] Solar rooftop: Perspective of DISCOMS (https://www.teriin.org/sites/default/files/2019-08/DUF_Solar-Rooftop.pdf)

4. Impact of Single-Phase Net Energy Metering on Load Curve

NEM in small numbers may not impact the demand and supply curve of the power sector. However, with more considerable penetration, NEM significantly impacts the load curve of the demand. Utility companies have to adjust their generation capabilities accordingly. This impact of NEM is typically called a 'duck curve'. For example, in figure 6, solar PV's impact on the load curve in California is depicted. The load curve in 2012 is without NEM. However, NEM started to add up in subsequent years. This reduces the daytime load of the utility company, and with each passing year, the successive addition of NEM causes the daytime peak to reduce even more. However, since the dip in load curve is only during daylight hours, the load shifts rapidly back to the grid in the evening hours. This phenomenon where the daytime load curve decreases but the evening-time load curve increases are called the duck curve. The duck curve impact is different everywhere depending on the NEM's location, season, penetration, and utility load profiles.

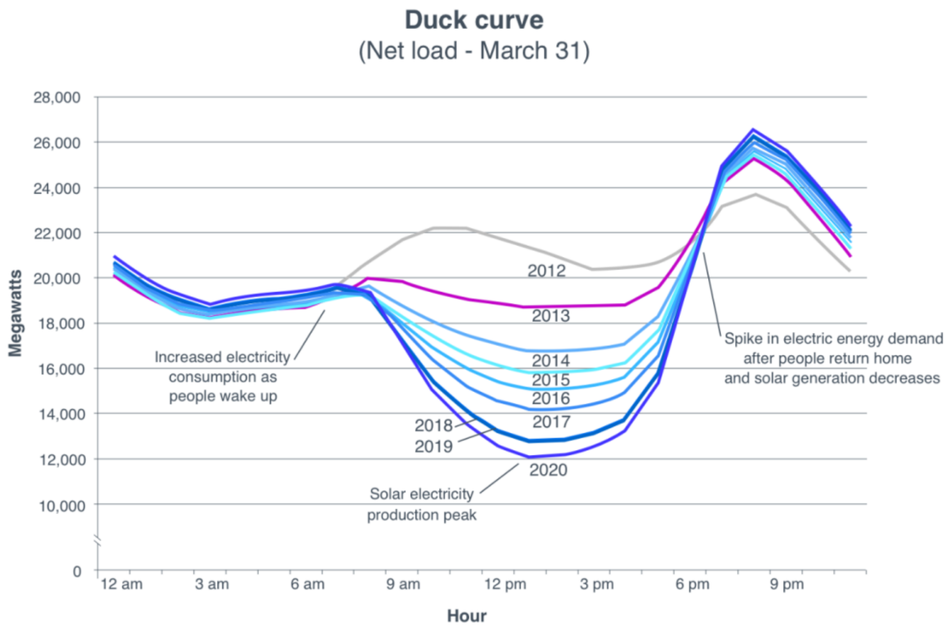


Figure 6. Solar PV impact on the load curve (California)

To assess duck curve impact on IESCO's load profile, we first estimate the solar PV penetration with 5%, 10%, 25%, and 50% of NEM connections in single-phase. The following table4 estimates the added solar PV generation in the IESCO network. Using these penetration cases, we estimate the duck curve impact on IESCO. Table 4 gives an overview of the single-phase connection in the IESCO network.

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

IESCO Stats		Solar Capacity		
Total Residential Connections	2,770,000	4 kW per house	MW Installed	Annual Generated Units (kWh)
Single-Phase Connections	2,647,000			
5% Single-Phase Consumers	132,350	529,400	529.4	784,623,757
10% Single-Phase Consumers	264,700	1,058,800	1058.8	1,569,247,515
25% Single-Phase Consumers	661,750	2,647,000	2647	3,923,118,786
50% Single-Phase Consumers	1,323,500	5,294,000	5294	7,846,237,573

4.1 Duck Curve Impact on Load Profiles

To evaluate the impact caused by a large number of single-phase consumers, we used actual load curves of four days in 2019 from four distinct seasons at IESCO. Figure 7 shows the solar irradiance in W/m^2 plotted with the load curve. We used the NREL PVWatts calculator to calculate the solar PV irradiance for the specified days at hourly granularity in Islamabad. Note that this is the coincidental load and not the sanctioned load of the IESCO. The sanctioned load of IESCO is approximately 4700MW for domestic customers but for a realistic assessment of the duck curve; we employed a coincidental load profile. 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).

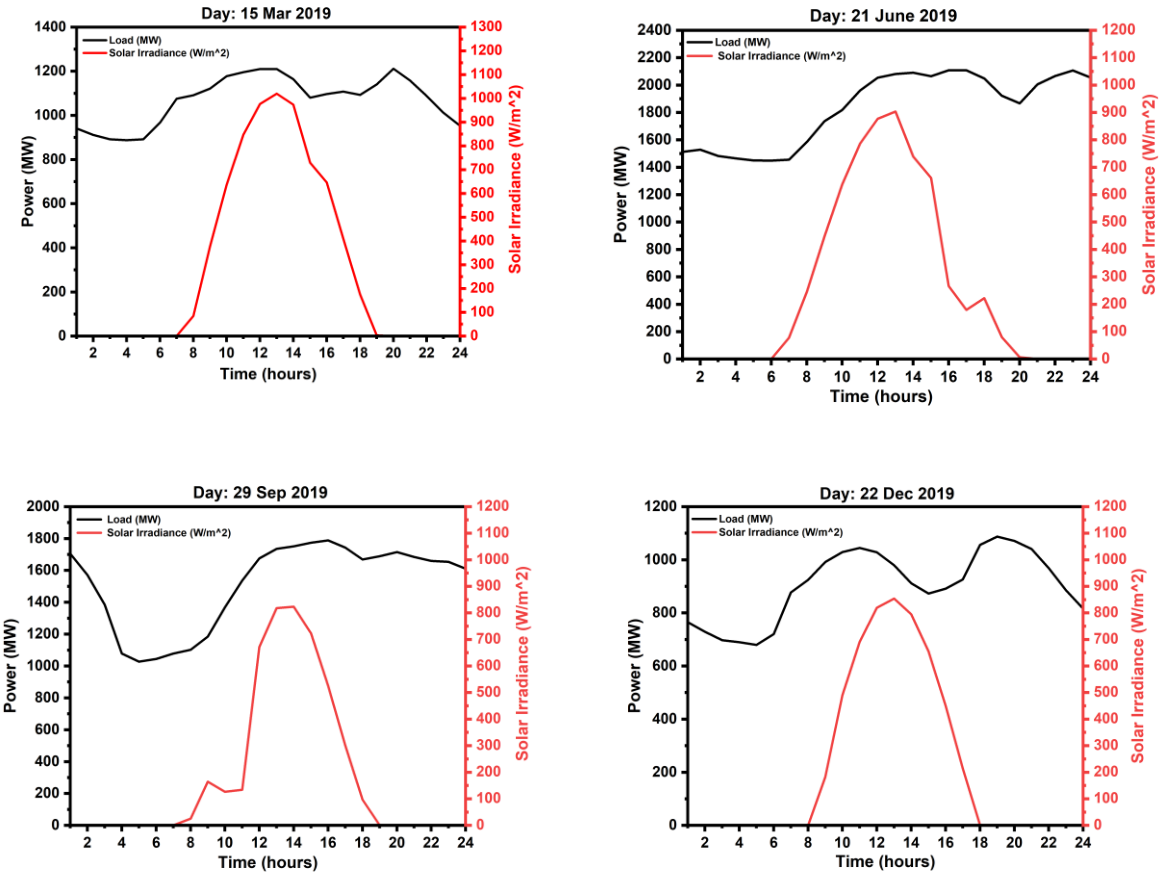


Figure 7. Load Curve along with Solar Irradiance (W/m2)

The impact on load curve with various penetration scenarios is depicted in figure 8. One can observe 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 to note 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. Not only are enough generation resources required, but generation resources with a high ramp rate will be required to meet the rapid surge in the load curve.

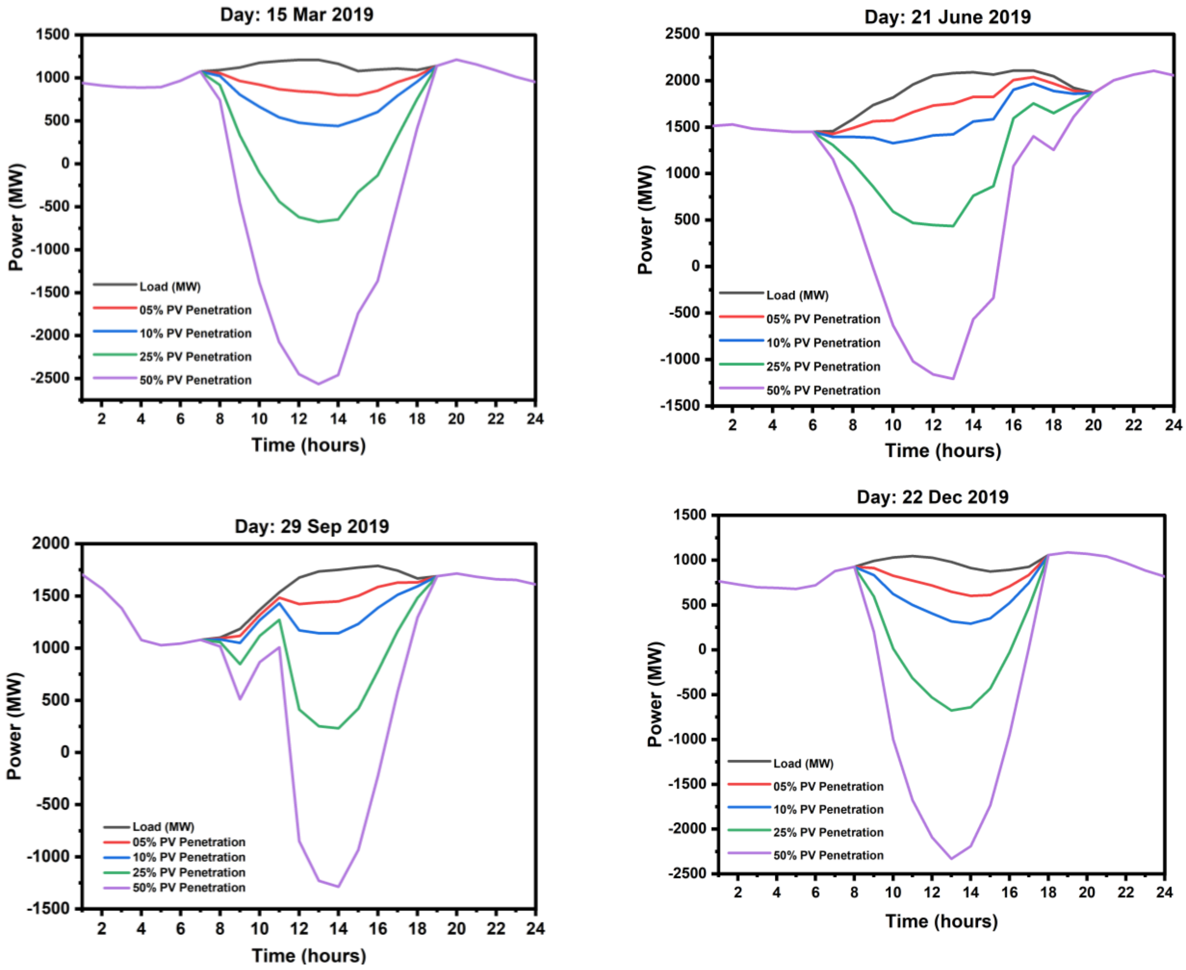


Figure 8. Duck Curve Impact on IESCO Network

Some technologies with efficient ramp-up rates are shown in table 5. Hydro resources provide the highest ramp rates, followed by fossil fuel-based generation sources.

Table 5. Efficient ramp up rates of different technology

Technology	MW/min
Combine Cycle Gas Turbine (CCGT)	10
Open Cycle Gas Turbines (OCGT)	20
Pump Hydro	200
Hydro Reservoir	150

With different solar penetrations, ramp rate requirement changes. The minute-level ramp rate required at different NEM penetration levels is given in table 6.

Table 6. Ramp up rates for different PV penetration for IESCO network

Ramp up Rate (MW/min)					
Solar Penetration (%)	15-Mar	21-Jun	29-Sep	22-Dec	Average
5%	0.855893	0.526449	0.806148	1.360262	0.887188
10%	1.904147	1.211752	1.818962	2.463856	1.849679
25%	5.048908	3.267662	4.857406	5.774641	4.737154
50%	10.29018	6.694179	9.921479	11.29262	9.549612

4.2 Duck Curve Mitigation Techniques

Unlike many countries, Pakistan has fewer industrial loads. This explains the highly visible impact of the duck curve in the IESCO example above. The duck curve presents a planning and despatch challenge. Various mitigation techniques are discussed in the literature to flatten the belly of the duck curve. However, DISCOs in Pakistan have their own limitations when it comes to the adoption of modern duck curve mitigation techniques. Following are some of the techniques that DISCOs may adopt to reduce the impact of the duck curve:

4.2.1 Smart Meter and Variable tariff

One of the methods to reduce the impact of the load curve is variable pricing. However, any type of variable pricing requires smart metering that records the load at small intervals. Smart meters provide a way for customers and DISCOs to communicate effectively for sending price signals. Price signals are the most effective way for customers to increase and decrease the load. Depending on domestic and industrial customers, different price signals may be designed.

To help control the duck curve, DISCOs may require smart installation with NEM. However, DISCOs should have the information technology tools to send price-based signals and other load and generation curtailing interventions.

4.2.2 Daytime Load Growth and Load Management

Another method to reduce the impact of the duck curve is through the shift of flexible loads to daytime hours. Some flexible loads such as water pumps, tube wells, and some industrial processes should only operate during the daylight hours to flatten the duck curve belly. Moreover, some other energy sectors such as cooking, water, and space heating that typically utilize natural gas may shift to the grid electricity. Pakistan is facing an acute shortage of indigenous natural gas and conversion to the electricity of gas-based loads may help relieve some pressure off the natural gas resources.

4.2.3 Grid to Vehicle Charging

Electric vehicles (EV) are being introduced in Pakistan. EV load will require significant electricity from the grid for charging. EVs is a flexible load and may be charged during the daytime. Therefore, EV tariffs may be provided for various charging levels of EVs to encourage charging during the daytime. This type of tariff will be beneficial for locations like offices where EVs are parked for a significant time during the day.

4.2.4 Energy Storage Systems

Reducing the duck curve is also possible with the installation of large-scale batteries. These batteries store solar energy during the day and use it during the evening to reduce the ramp rate requirement for the utility. However, due to the costly nature of the batteries, the storage capacity has yet to be successfully implemented at the residential scale. Storage must have a fleetwide duration of 100-1000 hours to offer reliable capacity during multi-day and multi-week periods of low renewable energy output. Current storage technologies, such as lithium-ion, cannot deliver this duration economically, and most only have capacities to last 1 to 10 hours.

4.2.5 Shifting to Direct Low Current-Voltage (DC home)

Having Direct Current (DC) distribution instead of Alternating Current (AC) can decrease the losses in the overall distribution system. This may also encourage the customers to have intelligent DC loads, e.g., DC air conditioners, DC motors, DC-based refrigerators. These DC loads will not place a burden on the grid in peak hours by avoiding inrush current as required by AC loads. A DC home with a modern DC load can mitigate the duck curve if coupled with intelligent meters.

5. Impact of Single-Phase Net Energy Metering on Distribution Network

NEM, in general, creates technical challenges for DISCOs. To assess the impact of single-phase NEM, we modeled an actual distribution transformer (DT) of IESCO. In this assessment, we assumed single-phase NEM installation at various connections. We used Electrical Transient Analyzer Program (ETAP) to model the network.

5.1 Modeling of Single-Phase Net Energy Metering Penetration in ETAP

We used the IESCO network to perform our modeling. The selected feeder network at IESCO is replicated using ETAP. In the feeder network, we selected a DT which consists of only single-phase connections. Figure 9 depicts the block diagram of the selected DT and its associated network. Table 6 lists the DT impedances that were used in the simulation. The connection configuration, actual number of houses connected to the DT, and the house's actual distance from the DT are all shown in table 7. In the simulation, the distribution transformer (DT) with a rating of 200kVA and its connected load is modeled, with the connections listed in table 7. At different phases, there are a total of fifty-seven houses connected to the transformer. Nineteen houses are connected to each phase. Table 8 shows the cumulative length of the connected buses from the DT in meters. The distance of the farthest house from the DT is 348 meters. Due to power loss in the conductor, the voltage drop on this bus was noted to be higher than other busses.

Table 6. Transformer impedance used in the ETAP simulation.

Transformer Impedance					
	%Z	**X/R**	**R/X**	**%X**	**%R**
Positive	4	1.5	0.667	3.328	2.219
Zero	4	1.5	0.667	3.328	2.219

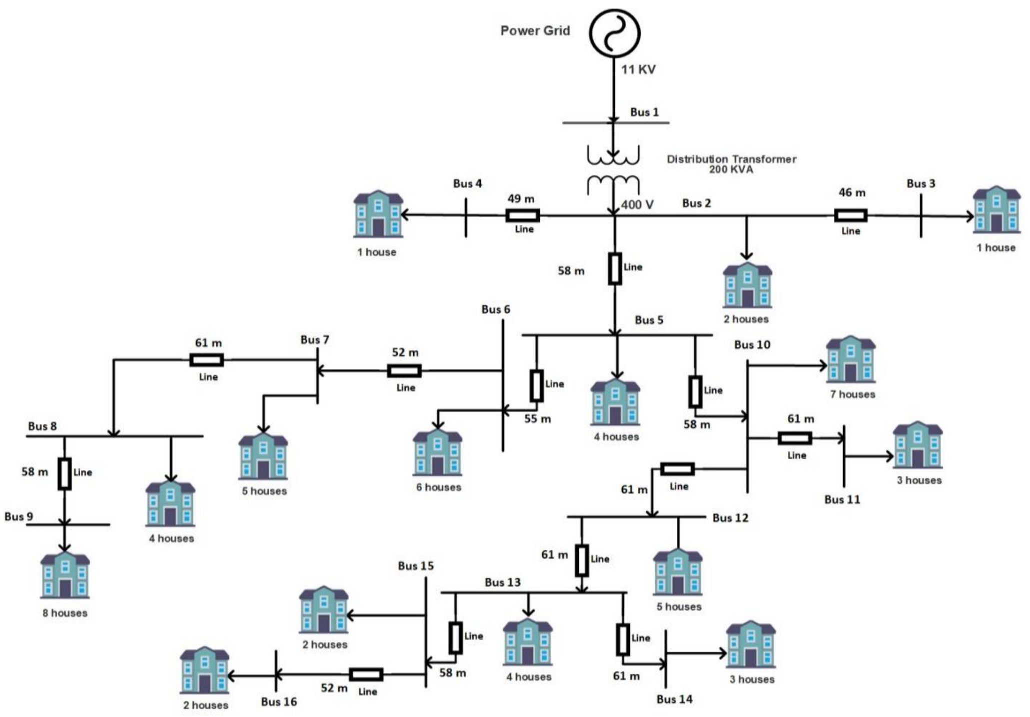


Figure 9. Block Diagram of IESCO Distribution System

Table 7. Assumed connection scheme, actual length (m), and actual no. of connected houses.

From Bus	To Bus	Actual Length (m)	Actual 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**

Table 8. Cumulative length (m) from the transformer secondary side

From Bus	To Bus	Cumulative Length (m)
1	2	0
2	3	46
2	4	49
2	5	58
2	6	113
2	7	165
2	8	226
2	9	284
2	10	116
2	11	177
2	12	177
2	13	238
2	14	299
2	15	296
2	16	348

5.2 Cases for Capacity Assessment

This study looked at six different cases, each consisting of five different scenarios. Each case has different consumption and has different sanctioned loads, as illustrated below:

Case A: Each house has a connected load of 0.2-0.4 kVA with sanctioned load of 2 kW.

Case B: Each house has a connected load of 1 kVA with sanctioned load of 1 kW.

Case C: Each house has a connected load of 2 kVA with sanctioned load of 3 kW.

Case D: Each house has a connected load of 3 kVA with sanctioned load of 4 kW.

Case E: Each house has a connected load of 2-4 kVA with sanctioned load of 2-4 kW.

Case F: Unbalanced Scenario

Each case has five scenarios linked to it, ranging from 0% to 50% PV penetration. If a total of N houses is connected to the feeder, then 5% penetration means that solar systems are assumed to be installed on 5% of N houses. Moreover, except case E, if *A* kWp solar is installed on one house, then total PV installed in 5% penetration will be

Total PV Installed capacity = *A* kWp * 5%N

The DT had different loading scenarios in each case. Figure 9 depicts a block schematic of the selected IESCO feeder distribution network, with entire line lengths and the number of houses connected to each bus. The system is comprised of 16 buses, each with a specific number of connected single-phase residential loads. Six different cases of solar PV penetration levels were taken to compare the voltage regulation at the point of standard coupling (PCC). After all the settings in ETAP, the unbalanced load flow study was conducted, and the system unbalance rates and transformer loading per phase were evaluated in table 10. The voltage at each bus was also calculated. The per-unit voltage at each bus was monitored. Each case has five scenarios with the following order of PV Penetration:

S1: 0% PV Penetration

S2: 5% PV Penetration

S3: 10% PV Penetration

S4: 25% PV Penetration

S5: 50% PV Penetration

In each case, the illustration of the finding and its discussion were addressed individually. Total PV feed-in for each case scenario wise is further shown in Appendix B.

5.2.1 Case A: 0.2-0.4 kVA Load on Each House

Each residential single-phase load, in this case, is in the range of 0.2-0.4 kVA, assuming that it is the winter load in Pakistan. The total load connected to the 200 kVA transformer is 16.7 kVA. There are five possible scenarios considering different solar PV penetration levels ranging from 0% to 50%. In this case, each house is considered to have a sanctioned load of 2 kW. The Power factor of each house is assumed to be 95%. The PV installed per house was taken to be 2 kW_p at 1000 W/m^2 irradiance.

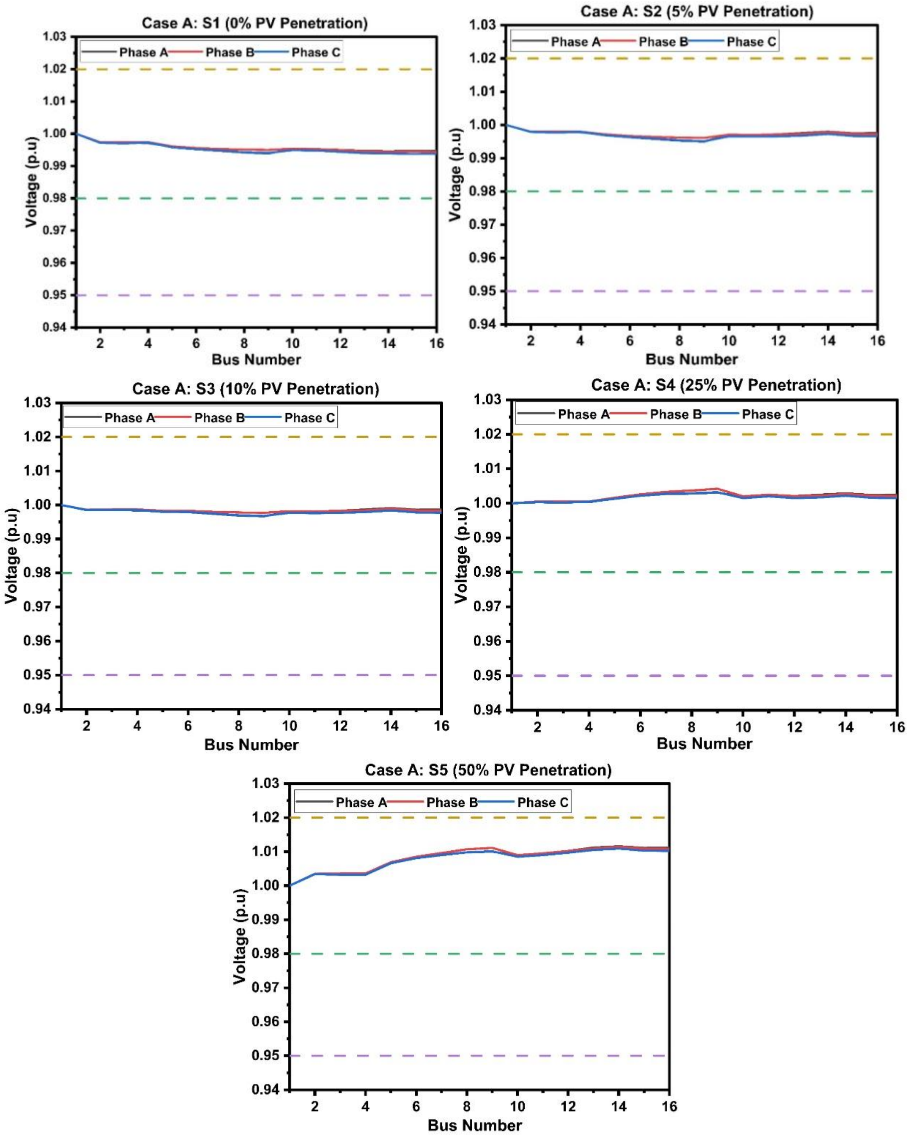


Figure 10. Case A: Per unit (p.u) voltage profile of the system with five scenarios from 0-50% PV Penetration

Figure 10 shows the per-unit voltage levels at each bus of different scenarios of Case A. The graphs demonstrate that the voltage regulation improved as the PV penetration increased, but a voltage rise appeared at 50% PV penetration, as seen in figure 10 (S5). However, the per-unit voltage increased was under the marginal overvoltage range. In this case, 0 to 50% PV penetration is not detrimental to the system because the per-unit voltage is within its limitations.

5.2.2 Case B: 1 kVA Load on Each House

Each residential single-phase load in Case B is 1 kVA. The total load connected to the 200 kVA transformer is 57 kVA. There are five possible scenarios considering different solar PV penetration levels ranging from 0% to 50%. In this case, each house is considered to have a sanctioned load of 1 kW. The Power factor of the house is assumed to be 95%. The PV installed per house is taken to be 1.07 kW_p at 1000 W/m^2 irradiance.

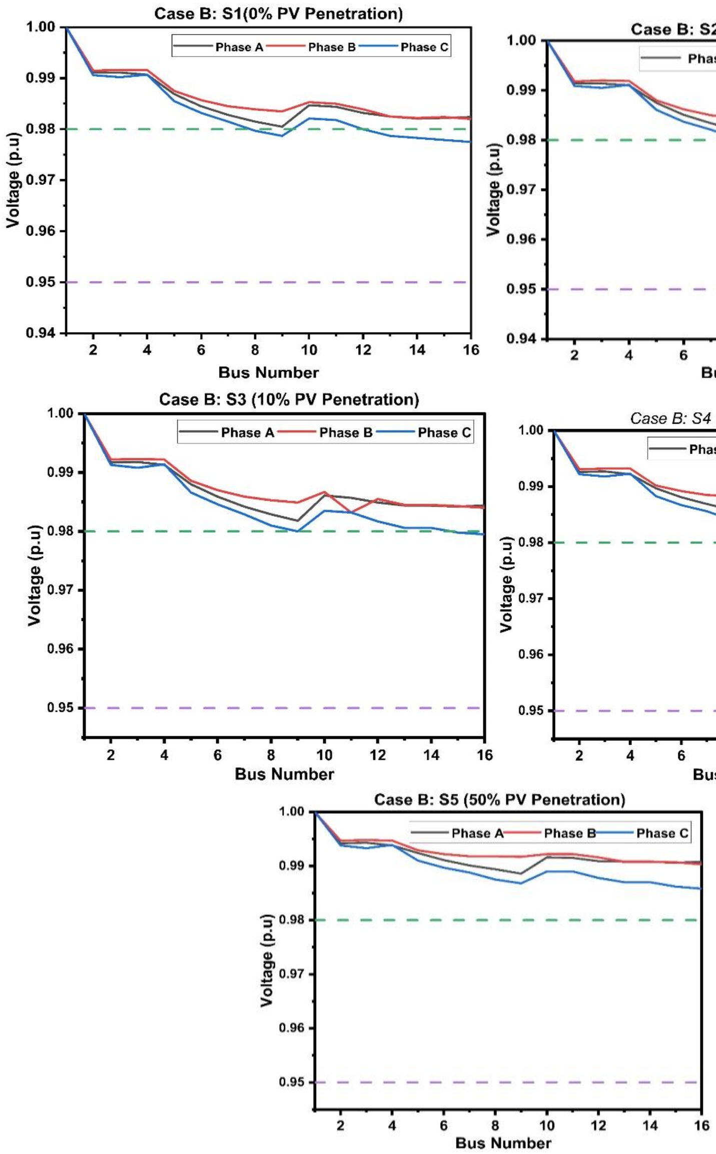


Figure 11. Case B: Per-unit (p.u) voltage profile of the system with five scenarios from 0-50% PV Penetration

Figure 11 shows the per-unit voltage levels at each bus of different scenarios of Case B. Figure 11 demonstrates that as the PV penetration increased, the voltage regulation improved respectively from marginal undervoltage to 1 p.u. In this case, 0 to 50% PV penetration is not detrimental to the system because the per-unit voltage is within its limitations.

5.2.3 Case C: 2 kVA Load on Each House

Each residential single-phase load in Case C is 2 kVA. The total load connected to the 200 kVA transformer is 114 kVA. There are five possible scenarios considering different solar PV penetration levels ranging from 0% to 50%. In this case, each house is considered to have a sanctioned load of 3 kW. The Power factor of the house is assumed to be 95%. The PV installed per house is taken to be 2.14 kW_p at 1000 W/m^2 irradiance.

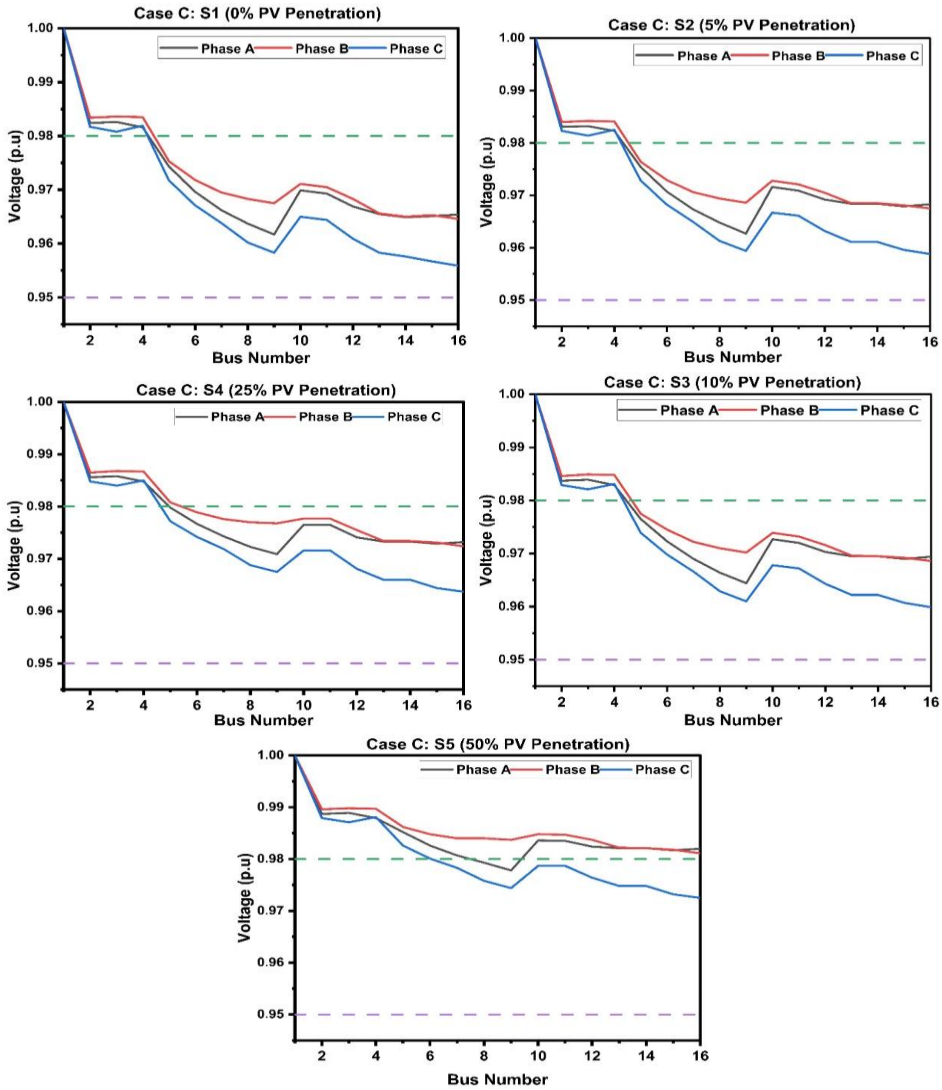


Figure 12. Case C: Per-unit (p.u) voltage profile of the system with five scenarios from 0-50% PV Penetration

Figure 12 shows the per-unit voltage levels at each bus of different scenarios of Case C.
Figure 12 demonstrates that as the PV penetration increased, the voltage regulation improved respectively from marginal undervoltage to 1 p.u. In this case, 0 to 50% PV penetration is not detrimental to the system because the per-unit voltage is within its limitations.

5.2.4 Case D: 3 kVA Load on Each House

Each residential single-phase load in Case D is 3 kVA. The total load connected to the 200 kVA transformer is 171 kVA. There are five possible scenarios considering different solar PV penetration levels ranging from 0% to 50%. In this case, each house is considered to have a sanctioned load of 4 kW. The Power factor of the house is assumed to be 95%. The PV installed per house is taken to be 3.21 kW_p at 1000 W/m^2 irradiance.

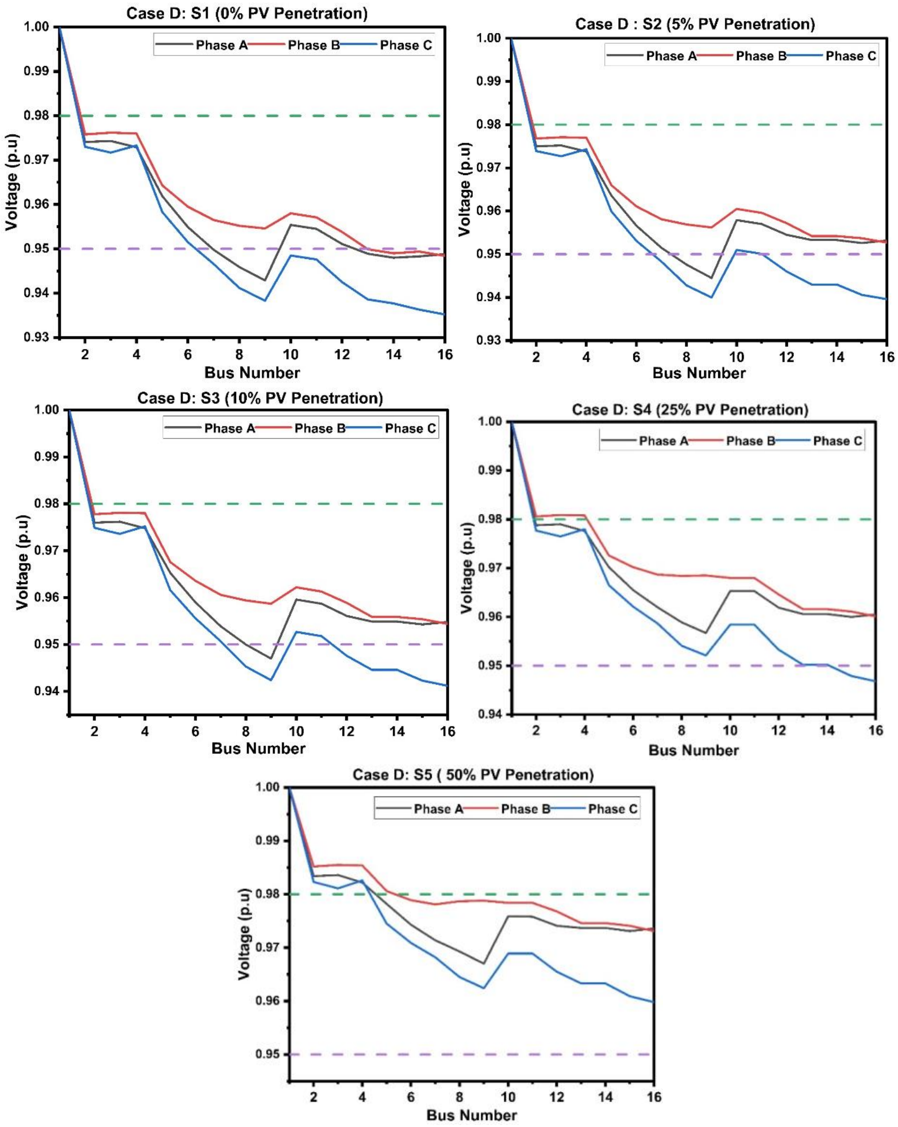


Figure 13. Case D: Per-unit (p.u) voltage profile of the system with five scenarios from 0-50% PV Penetration

Figure 13 shows the per-unit voltage levels at each bus of different scenarios of Case D. Because of the large total connected load, the per-unit voltage for the distant buses has dropped to a critically Undervoltage level. The graphs demonstrate that as the PV penetration increased, the voltage regulation improved respectively from critical undervoltage to relative marginal undervoltage level. In this case, 0 to 50% PV penetration is not detrimental to the system because the per-unit voltage is enhanced within its limitations.

5.2.5 Case E: 2-4 kVA Load on Each House

Each residential single-phase load, in this case, is in the range of 2-4 kVA, assuming that it is a summer load in Pakistan. The total load connected to the 200 kVA transformer is 162.1 kVA. There are five possible scenarios considering different solar PV penetration levels ranging from 0% to 50%. In this case, each house is deemed to have a sanctioned load of 2-4 kW. The Power factor of the house is assumed to be 95%. The PV installed per house is assumed to be 2.23-3.75 kW_p at 1000 W/m^2 irradiance according to their sectioned load.

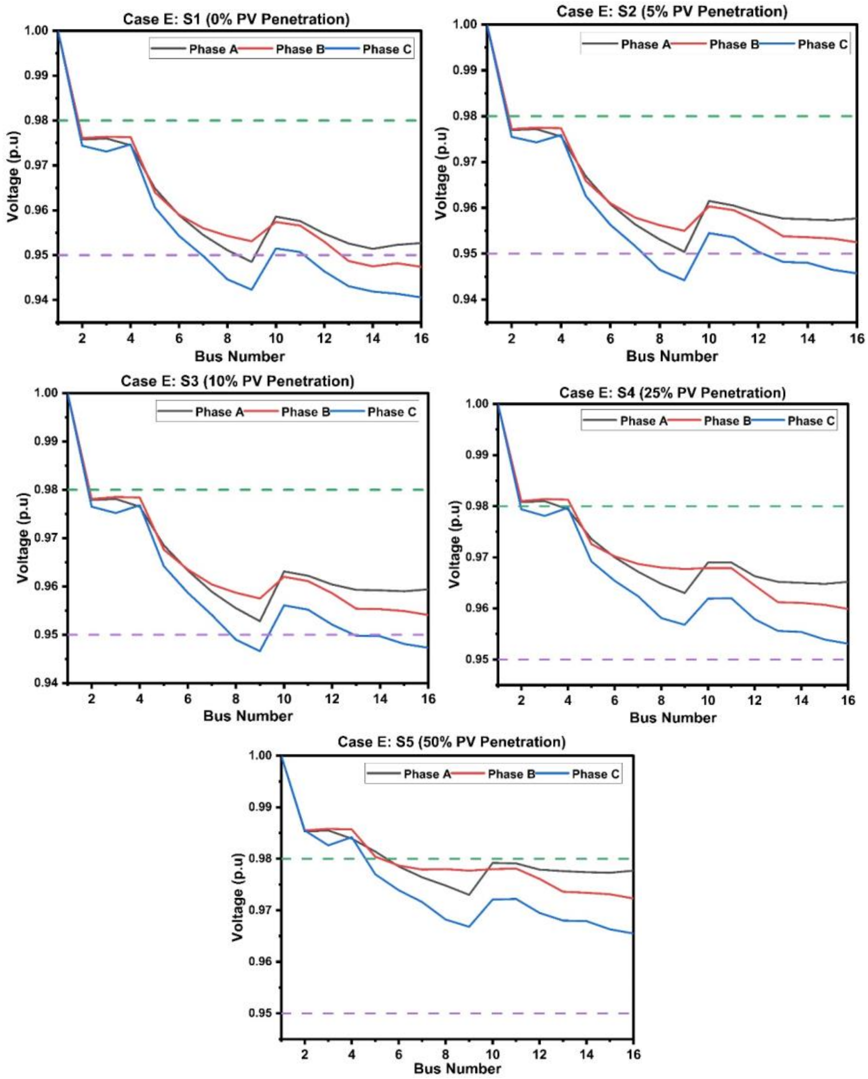


Figure 14. Case E: Per-unit (p.u) voltage profile of the system with five scenarios from 0-50% PV Penetration

Figure 14 shows the per-unit voltage levels at each bus of different scenarios of Case E. Because of the large total connected load, the per-unit voltage for the distant buses has dropped to a critically Undervoltage level. The graphs demonstrate that as the PV penetration increased, the voltage regulation improved from critical Undervoltage to relative marginal Undervoltage level. In this case, 0 to 50% PV penetration is not detrimental to the system because the per-unit voltage is enhanced within its limitations.

5.2.6 Case F: Unbalanced Scenario

In order to assess a scenario with the unequal solar photovoltaic installation, a particular case was designed in which 10 houses connected to the two phases (A and B) have solar installed while phase 3 has zero solar installation. Each residential single-phase load, in this case, is two kVA. The total load connected to the 200 kVA transformer is 114 kVA. The power factor of the house is assumed to be 95%. The PV installed per house is taken to be 2.14 kWp at 1000 W/m^2 irradiance. A total of 42.8 kWp solar has been installed in phase A and phase B. phase C has 0% PV penetration. Figure 15 shows the per-unit voltage levels at each bus in this case. The figure demonstrates that the phases' imbalance has been created due to significant differences in PV penetration. To avoid this unbalance, the PV must be installed at each phase in a consistent manner.

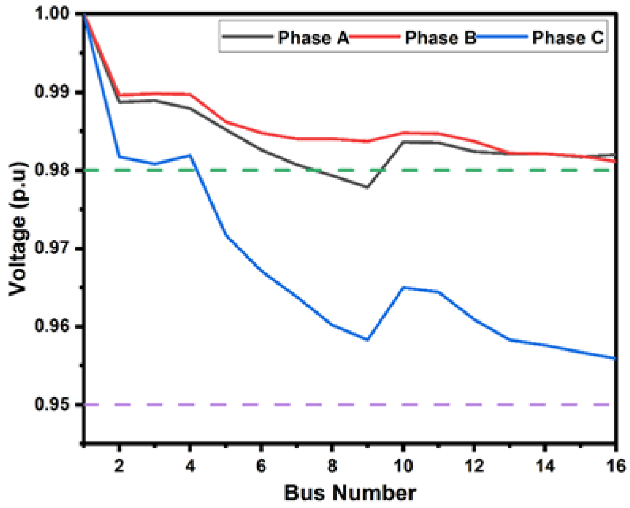


Figure 15. The per unit (pu) voltage profile for unequal solar installed among the three-phases.

5.3 Impact on Power Loss

NEM can help utilities get better control of the peak demand by levelling out the demand curve for electricity. By encouraging generation close to the point of use, NEM reduces the demand on distribution networks and prevents long-distance electricity transmission and distribution losses. Table 9 illustrates the power loss of the conductor, transformer, and overall system power loss for all cases and scenarios. The power loss is further divided into active, reactive, and apparent power loss, which are further demonstrated in detail in table 9. When the load is increased, the power loss also increases. Table 10 shows the transformer loading per phase for all cases and scenarios. As can be shown, case A has less loading per phase as compared to other cases. As observed from table 9, power losses from Case B to Case E with S1 towards S5 decreased due to load reduction into the power grid, and PV penetration increased from 0-50%. The load reduction per phase can be seen from table 10 as well. In Case A, at 50% PV penetration, power losses are increased because PV feed-in is high compared to other scenarios of Case A. The power losses are significant at 50% PV penetration in this case. Apart from Case A, power losses are lower at 50% PV penetration than in all cases in the S1 (0% PV penetration) scenarios. Case D with S1 has the most power loss in the conductor and transformer due to high loading per phase. In a nutshell, as the loading on the DT per phase is lowered, the system's power loss reduces. PV penetration will minimize the system's power loss in our cases and scenarios.

Table 9. Loss of conductor, transformer, and total system loss in active KW, reactive kVar and apparent KVA for all the cases and scenarios

Power Loss										
		Conductor 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	0.1	0.10	0.3	1	1.04	0.3	1.1	1.14
	S3 (10%)	0	0.1	0.10	0.3	0.9	0.95	0.3	1	1.04
	S4 (25%)	0	0.1	0.10	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

Table 10. Transformer Loading per Phase for all cases and scenarios.

Transformer Loading per Phase				
Cases	**Scenarios**	**Phase A (%)**	**Phase B (%)**	**Phase C (%)**
Case A	S1 (0%)	8.3	8	8.5
	S2 (5%)	5.7	5.4	5.9
	S3 (10%)	3.5	3.2	3.6
	S4 (25%)	6.7	7	6.6
	S5 (50%)	20.4	20.2	20.2
Case B	S1 (0%)	27.8	26.3	29.1
	S2 (5%)	26.4	25	27.8
	S3 (10%)	25.1	23.7	26.5
	S4 (25%)	21.2	19.8	22.6
	S5 (50%)	15.2	13.8	16.5
Case C	S1 (0%)	54.2	51.5	56.7
	S2 (5%)	51.6	48.9	54.1
	S3 (10%)	49	46.3	51.5
	S4 (25%)	41.4	38.6	43.9
	S5 (50%)	29.5	26.9	31.9
Case D	S1 (0%)	79.3	74.2	82.7
	S2 (5%)	75.5	70.3	78.9
	S3 (10%)	71.6	66.5	75
	S4 (25%)	60.4	55.2	63.8
	S5(50%)	43.1	38.1	46.3
Case E	S1 (0%)	74.1	73.6	78.5
	S2 (5%)	69.5	69.1	73.9
	S3 (10%)	65.7	65.2	70.1
	S4 (25%)	54.2	53.7	58.6
	S5 (50%)	37.6	37.1	41.9

5.4 Summary of Findings

In conclusion, single-phase NEM reduces power losses and improves voltage regulations. The loading on the transformer reduces as onsite generation provides support to the DT with local electricity generation. For extended DT networks, this can support the grid and solve problems of voltage dips at locations farther from the DT.

The addition of single-phase NEM on DT is not going to create a voltage imbalance issue as long as the NEM is distributed evenly on all three phases. If the DT network adds NEM without performing a balanced installation, some phases may overload and can create issues such as tripping and generation side issues.

6. Financial Impact of Single-Phase Net Energy Metering

The current NEM policy for single-phase consumers launched in Jan 2021 dictates that if a single-phase consumer wants to avail NEM, it has to upgrade from single phase to three-phase connection. Because the consumer is essentially on the three-phase connection after NEM, a fixed off-peak feed-in tariff of 16.33 PKR/kWh is used for NEM paybacks. In this section, we compare the three-phase NEM with the single-phase NEM. There are two options to calculate the financial impact of single-phase NEM. “Option 1” considers an off-peak feed-in tariff of 16.33 PKR/kWh, according to current NEM policy, and estimates the revenue shortfall, while “Option 2” takes an example feed-in tariff, i.e., 7.74 PKR/kWh. Both calculations are performed for the consumers having installations of 3 kWp and 4 kWp solar systems.

6.1 Financial Impact with current NEM policy

Single-phase NEM reduces the load at utility companies and creates revenue shortfall. To calculate the revenue loss, we used the financial data from IESCO. In comparison to other distribution companies, IESCO has a relatively high recovery rate. It has 27 million domestic customers, with 95.56% single-phase connections. To calculate the revenue impact, we use two cases of 4 kWp and 3 kWp of solar PV penetration.

The NEM feed-in tariff currently offered to single-phase NEM consumers is the same provided to a three phase-consumer after converting to a three-phase connection. The current policy provides the feed-in tariff at the standard off-peak rate of 16.33 PKR/kWh. The financial impact of the single-phase NEM consumers to the power sector and specifically to the IESCO has been shown in table 11 for 4 kWp solar systems and table 12 for 3 kWp solar systems.

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

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

Table 11 provides a detailed analysis of PV penetration and associated revenue shortfall with the 4 kW system installed. With 5% of consumers having such solar PV, IESCO will have 529.4 MW of distributed generation. In this scenario, the number of units generated by solar PV would be about 0.785 TWh per year. The estimated revenue shortfall of the power sector from IESCO will be PKR 0.96 billion. Similarly, with a 10% solar PV, revenue shortfall will be about PKR 1.92 billion of its domestic sector revenues. With 25% and 50% solar PV penetration, revenue loss will be about PKR 4.79 billion and PKR 9.59 billion, respectively.

Table 11: Annual Power sector revenue calculations with "Option 1" for 4 kW solar system

IESCO Stats. (Connections in millions)		Solar Capacity		Self-Consumption (400 kWh per month)	Number of Feed-In Units (kWh)	Power Sector Revenue (Billions PKR)		
Total Single Phase	**2.6**	**Total MW Installed**	**Generated Units (kWh)**			**Current Govt. Subsidy[10]**	**DISCO Payment to Prosumers with Option 1**	**Net Loss with Option 1**
5% Single Phase	0.13	529.4	784,623,757.3	635,280,000	149,343,757	**1.48**	**2.44**	**0.96**
10% Single Phase	0.26	1,058.8	1,569,247,515	1,270,560,000	298,687,515	**2.96**	**4.88**	**1.92**
25% Single Phase	0.66	2,647	3,923,118,786	3,176,400,000	746,718,786	**7.40**	**12.19**	**4.79**
50% Single Phase	1.32	5,294	7,846,237,573	6,352,800,000	1,493,437,573	**14.80**	**24.39**	**9.59**

[10] Single-phase consumers get a subsidy from the government for initial units. This is the subsidy the government gives to consumers in their initial slabs. With the conversion to a three-phase NEM, the government does not have to provide this subsidy.

For a 3 kW system, the assumptions taken are:

- Each single-phase house consumes 300 kWh per month
- Each single-phase house has a sanctioned load of 3 kW

Table 12 provides a detailed analysis of PV penetration and associated revenue benefits. With 5% of solar PV, IESCO will have 397 MW of distributed generation. In this scenario, the number of units generated by solar PV would be about 0.588 TWh per year. The estimated net benefit of the power sector from IESCO will be PKR 0.83 billion. Similarly, with a 10% solar PV, the net benefit will be about PKR 1.65 billion of its domestic sector revenues. The net benefit with 25% and 50% solar PV penetration will be about PKR 4.13 billion and PKR 8.26 billion, respectively.

Table 12: Annual Power sector revenue calculations with "Option 1" for 3 kW solar system

IESCO Stats. (Connections in millions)		Solar Capacity		Self-Consumption (300 kWh per month)	Number of Feed-In Units (kWh)	Power Sector Revenue (Billions PKR)		
Total Single-Phase	**2.6**	**Total MW Installed**	**Generated Units (kWh)**			**Current Govt. Subsidy**	**DISCO Payment to Prosumers with option 1**	**Net Benefit with Option 1**
5% Single Phase	0.13	397	588,467,817.97	476,460,000	112,007,818	**2.66**	**1.83**	**0.83**
10% Single Phase	0.26	794	1,176,935,635.95	952,920,000	224,015,636	**5.31**	**3.66**	**1.65**
25% Single Phase	0.66	1,985	2,942,339,089.87	2,382,300,000	560,039,090	**13.28**	**9.15**	**4.13**
50% Single Phase	1.32	3,971	5,884,678,179.75	4,764,600,000	1,120,078,180	**26.55**	**18.29**	**8.26**

6.2 Financial Impact of Single-phase NEM Policy with Example Feed-in Tariff

As three-phase consumers are not provided electricity at subsidized rates, the NEM feed-in tariff for a three-phase consumer is 16.33 PKR/kWh during off-peak hours. This is too high for a single-phase consumer who is already purchasing electricity at subsidized rates. It can be seen in figure 16 that the applicable tariff slabs, according to the new regulations of DISCOs, provide a considerable amount of subsidy to the single-phase consumer. But the NEM feed-in tariff that is currently offered to single-phase NEM consumers is the same provided to a three phase-consumer. Assuming single-phase consumers can have NEM through single-phase inverters on a single-phase connection rather than shifting to a three-phase connection, the feed-in tariff structure should be redesigned. Such an example tariff can reduce the financial loss shown in the previous section and might also help to generate more revenue for DISCOs.

The net benefit has been calculated for assuming each single-phase consumer installs a 4 kWp solar system, assuming

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 consumer will be given the benefits of only one previous slab						

Figure 16: Slab based tariff for a single-phase consumer

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

Table 13 provides a detailed analysis of PV penetration and associated revenue benefits. With 5% of solar PV, IESCO will have 529.4 MW of distributed generation. In this scenario, the number of units generated by solar PV would be about 0.785 TWh per year. The net benefit estimated of the power sector from IESCO will be PKR 0.32 billion. Similarly, with a 10% solar PV, revenue shortfall will be about PKR 0.65 billion of its domestic sector revenues. The net benefit with 25% and 50% solar PV penetration will be about PKR 1.62 billion and PKR 3.24 billion, respectively.

Table 13: Annual Power sector revenue calculations with "Option 2" for 4 kW solar system

IESCO Stats. (Connections in millions)		Solar Capacity		Self-Consumption (400 kWh per month)	Number of Feed-In Units (kWh)	Power Sector Revenue (Billions PKR)		
						Current Govt. Subsidy	DISCO Payment to Prosumers with Option 2	Net Benefit with Option 2
Total Single-Phase	2.64	Total MW Installed	Generated Units (kWh)					
5% Single Phase	0.13	529.4	784,623,757.3	635,280,000	149,343,757	**1.48**	**1.16**	**0.32**
10% Single Phase	0.26	1,058.8	1,569,247,515	1,270,560,000	298,687,515	**2.96**	**2.31**	**0.65**
25% Single Phase	0.66	2,647	3,923,118,786	3,176,400,000	746,718,786	**7.40**	**5.78**	**1.62**
50% Single Phase	1.32	5,294	7,846,237,573	6,352,800,000	1,493,437,573	**14.80**	**11.56**	**3.24**

For a 3 kW system, the assumptions taken are

- Each single-phase house consumes 300 kWh per month
- Each single-phase house has a sanctioned load of 3 kW

Table 14 provides a detailed analysis of PV penetration and associated revenue benefits for a 3 kW system. With 5% of solar PV, IESCO will have 397 MW of distributed generation. In this scenario, the number of units generated by solar PV would be about 0.588 TWh per year. The estimated net benefit of the power sector from IESCO will be PKR 1.79 billion. Similarly, with a 10% solar PV, the net benefit will be about PKR 3.58 billion of its domestic sector revenues. The net benefit with 25% and 50% solar PV penetration will be about PKR 8.94 billion and PKR 17.89 billion, respectively.

Table 14: Annual Power sector revenue calculations with "Option 2" for 3 kW solar system

IESCO Stats. (Connections in millions)		Solar Capacity		Self-Consumption 300 kWh per month	Number of Feed-In Units (kWh)	Power Sector Revenue (Billions PKR)		
Total Single Phase	2.64	Total MW Installed	Generated Units (kWh)			Current Govt. Subsidy	DISCO Payment to Prosumers with option 2	Net Benefit with Option 2
5% Single Phase	0.13	397	588,467,817.97	476,460,000	112,007,818	**2.66**	**0.87**	**1.79**
10% Single Phase	0.26	794	1,176,935,635.95	952,920,000	224,015,636	**5.31**	**1.73**	**3.58**
25% Single Phase	0.66	1,985	2,942,339,089.87	2,382,300,000	560,039,090	**13.28**	**4.33**	**8.94**
50% Single Phase	1.32	3,971	5,884,678,179.75	4,764,600,000	1,120,078,180	**26.55**	**8.67**	**17.89**

6.3 Additional Cost Due to Distribution Network Upgradation

DISCOs have to carry out certain system upgrades when the PV penetration rate rises to allow seamless system operation. Some of these upgrades are mentioned below:

1. Smart meters must be installed at various voltage levels to assess the system demand profile.
2. Distribution transformers capacity has to be enhanced with high solar PV penetration.
3. DISCOs need to develop an improved connection scheme for a better understanding of phase connections.
4. A geographic Information System (GIS) may be developed at the distribution level to see the physical map of distributed generation.
5. DISCOs may need to increase or decrease the conductor capacity according to PV penetration to avoid power losses and ensure high efficiency.
6. DISCOs may also need to carry out different types of laboratory tests to ensure that the inverter standards comply with established standards.
7. An investment in software tools is required for better solar PV forecasting and for better planning and development.

7. Recommendation for Single-phase Net Energy Metering in Pakistan

Based on best practices of single-phase NEM, research literature, and interviews with DISCO personnel following four sets of recommendations should be considered to make single-phase NEM a success in Pakistan.

7.1 Technical Studies

To make single-phase NEM a success without impacting the technical operations of the grid, a few studies should be carried out. These studies belong to the NEM site location as well as feeder and DT level studies to ensure that NEM operates seamlessly. Additionally, before allowing single-phase NEM standards and specifications of components such as inverters, power control units, conductors, lightning arrestors, energy meters, and data loggers should be finalized based on state-of-the-art international best practices. More importantly, components must comply with the standards and regulations. As the number of consumers for single-phase NEM is much higher, the standard-compliant components and technical studies will promise safe and reliable operation of the grid:

7.1.1 Pre and Post Installation Survey

A pre-and post-installation survey must be carried out for single-phase NEM. Similarly, periodic checks should be carried out at regular intervals. Pre-installation surveys should include checks such as space and bill assessment. The post-installation survey should check inverter specifications, earthing requirements, conductors, energy meters, and lightning arrestors. Both pre-and post-installation surveys are included in the current NEM regulations and should also be carried in single-phase NEM. However, periodic visits are not included in the current NEM regulations. DISCOs have no insight if a consumer changes the configuration or even add more adds more solar power. Similarly, the consumer can compromise safety measures if a solar PV upgrade is carried out for components that need periodic replacement. Therefore, periodic visits will allow the DISCOs to keep the NEM compliant with regulations.

7.1.2 Ensuring Power Balance

The single-phase NEM, unlike three-phase NEM, can create voltage imbalances. To avoid voltage imbalances, NEM must be installed on a phase such that solar PV in the DT is fairly divided amongst three phases. If a particular phase has more solar PV, then a balancing exercise should be carried out to keep solar PVs fairly distributed across the three phases. DISCOs have upper limits on imbalances as specified in the distribution code. Therefore, the solar PV should be distributed across phases such that the permitted imbalance ratio is not violated.

Load flow studies should be carried out at DTs where the number of NEM crosses a specific limit. Such studies will enable DISCOs to put a cap on the NEM connections based on the network capacity. This will also help the DISCOs to encourage NEM installation at locations where voltage regulation is a challenge due to long distances from DTs.

In rural setups, ‘feeder segregation’ is a technique used to provide reliable and quality electricity to non-agriculture consumers. This technique separates non-agricultural users from agricultural users, so that interruption in the electrical supply of agricultural users should not affect the non-agricultural consumers such as schools, houses, hospitals, etc. Using this technique, houses that are far away from the distribution system, which faces the problems of low voltages, can be separated. DISCOs may provide incentives for such customers to install NEM connections.

7.1.3 Use of ICT Tools

A significant penetration of single-phase NEM is not effectively possible without using appropriate ICT tools. The ICT tools will help DISCOs in a multitude of ways. A smart meter may provide the DISCOs with a way to communicate and monitor the NEM sites.

High granularity data collection from NEM sites is only possible through ICT tools. This data includes the load and generation profiles of NEM for better optimization and planning at DISCOs. Moreover, the data can help DISCOs design new tariff models for NEM, providing a win-win situation for both DISCOs and consumers. The data will also help DISCOs in load forecasting to plan better despatch and unit commitment for its generation contracts. DISCOs can also adjust power factors by adjusting the reactive power of the NEM site. ICT tools may provide better maintenance through fault prediction and reduced complaint redressal time. Also, NEM can create a generation imbalance and needs to be curtailed during emergency situations. Through ICT tools, DISCOs would be able to disconnect NEMs in a crisis situation to ensure reliable and safe operation of the grid.

Geographic Information Systems (GIS) at the distribution level can help the DISCOs to keep the network updated. GIS will also allow DISCOs to identify locations where NEM should be encouraged. Specific off-the-shelf ICT tools are available for addressing the challenges of single-phase NEM. For example, Future Grid and Envelio are a couple of digitalization tools for NEM adoption and other DISCO-related management.

7.2 Enhanced business models

Capital Expenditure Model (CAPEX):

In Pakistan NEM business model is at its initial stages. Presently, the CAPEX model is followed, which is a consumer anchored model. In this model, the consumer fully invests in the NEM. However, this method is only significant to those having a large amount of capital investment available. This model can seriously impede the growth of NEM. CAPEX is the only model that is adopted and permitted by the country.

Renewable Energy Service Company (RESCO):

To get the most out of NEM, Pakistan needs to adopt a more user-friendly business model such as the RESCO model, which is slowly getting traction in Pakistan but still is not mainstream. RESCO is the third-party investor who provides the following categories to enable NEM at the client's location:

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,

Utility Anchored:

Utility anchored business models can help reduce risks, improve system cost-performance, and make NEM technologies scalable. Utility anchored business models may be merged with RESCO or customer anchored models to get the benefits enhanced for both the consumer and the utility. Utility Anchored Models are based on demand aggregation, On-bill financing, and payment assurance.

Community Anchored

The community anchored model refers to local solar facilities shared by multiple community members who receive credit on their electricity bills for their share of the power produced. This model allows a community to pool in roof space, investment, and usage to develop a coop of solar demand and supply. Currently, this is the most popular model of solar PV in the USA.

7.3 New Regulations to Enable Single-phase Net Energy Metering

NEM policy in Pakistan is appropriate for three-phase NEM. However, some new regulations are needed to guarantee the safe operation of single-phase NEM.

First, the export from NEM should be limited. A large number of single-phase NEM can create power imbalances. Thus, energy export from NEMs should be capped with solar export limiters. Modern inverters have a built-in feature of the solar export limiter. Initially, a fixed limit may be required, but as the network becomes modern and robust, the cap can be adjusted based on the grid requirements.

Second, practices for power imbalances are not followed at DISCOs. With single-phase NEM, it should be made mandatory to assess the phase imbalances and guarantee fair solar PV distribution amongst phases

7.4 Customer Awareness and Marketing

DISCOS should start a consumer awareness campaign in their locale, emphasizing its benefits and advantages. By giving consumers a choice among reputable solar developers and ensuring quality, a structure for grading and impaneling developers could help to accelerate the uptake of solar rooftop systems. It would assist in enhancing consumer confidence and give DISCOs more promise about the quality of solar rooftop systems connected to their distribution network.

8. Conclusion

Rooftop solar systems are likely to rise in popularity and decrease in cost in the future. It is worth remembering that, unlike thermal power plants, NEM (single or three-phase) is dominated by customer-owned onsite generation. Therefore, public participation and acceptance are vital for its success. Manufacturing capacity, R&D investment, an investor-friendly climate, talent development, low-voltage grid connectivity of variable solar resources, and regulatory decisions are all critical issues that must be addressed at the national level. As rooftop solar penetration grows, manufacturing capability for solar modules can be established in Pakistan.

When solar PV penetration increases in LV single-phase distribution networks, voltage fluctuations may occur. This is especially important in residential single-phase systems due to voltage imbalances generated by the solar PV system into the network. It is essential to investigate single-phase PV power feed-in levels when residential net-metered solar PV numbers rise before voltage unbalances exceed standard limitations. In this study, an IESCO reference feeder network was employed, and the ETAP simulator was used to model various levels of PV penetration on the single phase. PV systems are connected in an even phase distribution, but each phase is loaded differently and at different points throughout the feeder length. As solar PV penetration rises from 0 to 50 %, IESCO's revenue loss increases. Each single-phase NEM coupled with a 4-kW solar PV system, IESCO's revenue loss would be more significant than its complete recovery. Around 156 % loss at 50% PV penetration is estimated. However, it can be concluded that since most of the feeders of Pakistan's distribution companies are operating under overloaded conditions, therefore, an increase in PV penetrations certainly relieves these overloading conditions, reduces the losses, and improves the voltage level within the distribution code limits. Hence, if proposed measures /recommendations are adopted, the revenue loss can certainly be minimized.

Based on carefully plotted results, recommendations and guidelines have also been provided for solar systems distributors and electricity distribution companies to ensure the orderly and sustainable development of Pakistan's single-phase net-metered DG markets.

9. Appendix A

Quotation and payback period of different sizes of PV panels systems

- **3kW**

Solar System: On-Grid				
3.115 kW PV Modules + 1 x 5 kW On-Grid Inverter(s)				
#	Parts	Specs	QTY	Price (PKR)
1	PV Modules (Mono PERC) - Jinko Solar	445 Wp	7	155,800
2	Mounting Structure - Fixed Frame	Galvanized Iron	3.5	15,400
3	On Grid Inverter - SunGrow	SG 5 KTL-MT	1	209,800
4	Inverter Manager / Comm Device	WiFi Enabled	Included	
5	Conductors, Ducting, and Accessories	/	Job	121,000
6	Protective Equipment (Breakers, SPD, etc.)	/	Job	
7	Transportation	/	Included	
Total Amount				502,000
OPTIONAL ITEMS				
1	Civil Works (for Mounting Structure)		Job	16,000
2	Smart Meter - SunGrow - w/CT's - built-in	50kA-3	Set	48,000
3	Net Energy Metering (Inspection, Documentation, Modifications, etc.)		<20 kW	83,500
Net Total				649,500

Payback

Year	Utilized Energy (KWh)	Grid Electricity Price (PKR)	Annual Cost Saving (PKR)	Annual Maint. Cost (PKR)	Net Cost Saving (PKR)	Cumulative Saving (PKR)
1	4,370	18.5	80,800	6,500	74,300	74,300
2	4,340	19.4	84,300	6,800	77,500	151,800
3	4,310	20.4	87,900	7,100	80,800	232,600
4	4,280	21.4	91,700	7,500	84,200	316,800
5	4,250	22.5	95,600	7,900	87,700	404,500
6	4,220	23.6	99,600	8,300	91,300	495,800
7	4,190	24.8	103,900	8,700	95,200	591,000
8	4,161	26.0	108,300	9,100	99,200	690,200
TOTAL (25yrs)	100,500		3,490,000	310,000	3,180,000	

- **4kW**

Solar System: On-Grid				
4.005 kW PV Modules + 1 x 5 kW On-Grid Inverter(s)				
#	Parts	Specs	QTY	Price (PKR)
1	PV Modules (Mono PERC) - Jinko Solar	445 Wp	9	200,300
2	Mounting Structure - Fixed Frame	Galvanized Iron	4.5	19,800
3	On Grid Inverter - SunGrow	SG 5 KTL-MT	1	209,800
4	Inverter Manager / Comm Device	WiFi Enabled	Included	

5	Conductors, Ducting, and Accessories	/	Job	121,000
6	Protective Equipment (Breakers, SPD, etc.)	/	Job	
7	Transportation	/	Included	
Total Amount				550,900
OPTIONAL ITEMS				
1	Civil Works (for Mounting Structure)		Job	16,000
2	Smart Meter - SunGrow - w/CT's - built-in	50kA-3	Set	48,000
3	Net Energy Metering (Inspection, Documentation, Modifications, etc.)		<20 kW	83,500
Net Total				698,400

Payback

Year	Utilized Energy (KWh)	Grid Electricity Price (PKR)	Annual Cost Saving (PKR)	Annual Maint. Cost (PKR)	Net Cost Saving (PKR)	Cumulative Saving (PKR)
1	5,610	18.5	103,800	7,000	96,800	96,800
2	5,570	19.4	108,200	7,400	100,800	197,600
3	5,530	20.4	112,800	7,800	105,000	302,600
4	5,490	21.4	117,600	8,200	109,400	412,000
5	5,450	22.5	122,500	8,600	113,900	525,900
6	5,410	23.6	127,700	9,000	118,700	644,600
7	5,370	24.8	133,100	9,500	123,600	768,200
8	5,332	26.0	138,800	10,000	128,800	897,000
TOTAL (25yrs)	129,000		4,473,000	339,000	4,134,000	

- **5kW**

Solar System: On-Grid				
5.34 kW PV Modules + 1 x 5 kW On-Grid Inverter(s)				
#	Parts	Specs	QTY	Price (PKR)
1	PV Modules (Mono PERC) - Jinko Solar	445 Wp	12	267,000
2	Mounting Structure - Fixed Frame	Galvanized Iron	6	26,400
3	On Grid Inverter - SunGrow	SG 5 KTL-MT	1	209,800
4	Inverter Manager / Comm Device	WiFi Enabled	Included	
5	Conductors, Ducting, and Accessories	/	Job	121,000
6	Protective Equipment (Breakers, SPD, etc.)	/	Job	
7	Transportation	/	Included	
Total Amount				624,200
OPTIONAL ITEMS				
1	Civil Works (for Mounting Structure)		Job	16,000
2	Smart Meter - SunGrow - w/CT's - built-in	50kA-3	Set	48,000

3	Net Energy Metering (Inspection, Documentation, Modifications, etc.)	<20 kW	83,500
Net Total			771,700

Billing

Year	Utilized Energy (KWh)	Grid Electricity Price (PKR)	Annual Cost Saving (PKR)	Annual Maint. Cost (PKR)	Net Cost Saving (PKR)	Cumulative Saving (PKR)
1	7,480	18.5	138,400	7,700	130,700	130,700
2	7,430	19.4	144,300	8,100	136,200	266,900
3	7,380	20.4	150,500	8,500	142,000	408,900
4	7,330	21.4	157,000	8,900	148,100	557,000
5	7,280	22.5	163,700	9,300	154,400	711,400
6	7,230	23.6	170,700	9,800	160,900	872,300
7	7,180	24.8	178,000	10,300	167,700	1,040,000
8	7,130	26.0	185,600	10,800	174,800	1,214,800
TOTAL (25yrs)	**172,500**		**5,979,500**	**366,500**	**5,613,000**	
		Monthly Saving (in the first year):		**10,900**		
		Payback Period (years)		**5.37**		

Payback

Year	Utilized Energy (KWh)	Grid Electricity Price (PKR)	Annual Cost Saving (PKR)	Annual Maint. Cost (PKR)	Net Cost Saving (PKR)	Cumulative Saving (PKR)
1	7,480	18.5	138,400	7,700	130,700	130,700
2	7,430	19.4	144,300	8,100	136,200	266,900
3	7,380	20.4	150,500	8,500	142,000	408,900
4	7,330	21.4	157,000	8,900	148,100	557,000
5	7,280	22.5	163,700	9,300	154,400	711,400
6	7,230	23.6	170,700	9,800	160,900	872,300
7	7,180	24.8	178,000	10,300	167,700	1,040,000
8	7,130	26.0	185,600	10,800	174,800	1,214,800
TOTAL (25yrs)	**172,500**		**5,979,500**	**366,500**	**5,613,000**	

10. Appendix B

Table B1: Total PV feed-in out of total load in %age for the five scenarios

Case A

Case	Scenarios	Phase	Load (kW)	PV feed-in of total load (%)
Case A	**S2 (5%)**	A	5.30	35.85
		B	5.10	37.25
		C	5.40	35.19
	S3 (10%)	A	5.30	71.70
		B	5.10	74.51
		C	5.40	70.37
	S4 (25%)	A	5.30	179.25
		B	5.10	186.27
		C	5.40	175.93
	S5 (50%)	A	5.30	358.49
		B	5.10	372.55
		C	5.40	351.85

Case B

Case	Scenarios	Phase	Load (kW)	PV feed in of total load (%)
Case B	**S2 (5%)**	A	17.50	5.43
		B	16.60	5.72
		C	18.30	5.19
	S3 (10%)	A	17.50	10.86
		B	16.60	11.45
		C	18.30	10.38
	S4 (25%)	A	17.50	27.14
		B	16.60	28.61
		C	18.30	25.96
	S5 (50%)	A	17.50	54.29
		B	16.60	57.23
		C	18.30	51.91

Case C

Case	Scenarios	Phase	Load (kW)	PV feed in of total load (%)
Case C	**S2 (5%)**	A	34.00	5.59
		B	32.30	5.88
		C	35.33	5.38
	S3 (10%)	A	34.00	11.18
		B	32.30	11.76
		C	35.33	10.76
	S4 (25%)	A	34.00	27.94
		B	32.30	29.41
		C	35.33	26.89
	S5 (50%)	A	34.00	55.88
		B	32.30	58.82
		C	35.33	53.78

Case D

Case	Scenarios	Phase	Load (kW)	PV feed in of total load (%)
Case D	**S2 (5%)**	A	49.40	5.77
		B	46.40	6.14
		C	51.20	5.57
	S3 (10%)	A	49.40	11.54
		B	46.40	12.28
		C	51.20	11.13
	S4 (25%)	A	49.40	28.85
		B	46.40	30.71
		C	51.20	27.83
	S5 (50%)	A	49.40	57.69
		B	46.40	61.42
		C	51.20	55.66

Case E

Case	Scenarios	Phase	Load (kW)	PV feed-in of total load (%)
Case E	**S2 (5%)**	A	46.30	7.17
		B	46.00	7.22
		C	48.70	6.82
	S3 (10%)	A	46.30	13.32
		B	46.00	13.41
		C	48.70	12.67
	S4 (25%)	A	46.30	32.40
		B	46.00	32.61
		C	48.70	30.80
	S5 (50%)	A	46.30	62.20
		B	46.00	62.61
		C	48.70	59.14