Assessing the Techno-Commercial Impact of Distributed Solar Energy Generation

A Case Study for Tamil Nadu

AurovilleConsulting

Sustainable Energy Transformation Series

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EXECUTIVE SUMMARY

For the purpose of providing policy recommendations to Tamil Nadu's electricity sector in the context of India's renewable energy targets, this study analyses the techno-commercial impact of introducing distributed solar energy generation at the distribution network level.

- Two separate deployment scenarios with different solar energy penetrations were analyzed: Utility Category solar (gross feed-in mechanisms) at the HT (high tension) feeder level and Consumer Category solar (net feed-in mechanisms) at LT (low tension) feeder level. Three different solar energy penetration levels were explored: 40%, 70% and a 100% solar energy penetration on total annual energy consumption.
- The technical impact analysis includes voltage, reactive power, feeder current capacity, distribution losses, and upstream grid dependency. For the financial impact analysis, TANGEDCO's (Tamil Nadu Generation and Distribution Corporation Limited) cost of supply (CoS) and net revenue were considered. In addition to solar, the impacts of introducing Time-of-Day (ToD) tariffs and energy storage were simulated.
- For assessing the impact of Utility Category solar at HT feeder level, ten feeders of Erode substation were analyzed with hourly interval data for the year 2018.
- For the impact assessment of Consumer Category solar on the LT feeder level, data for a single distribution transformer connected to Erode substation was available and analyzed.

Voltage fluctuations at the receiving end of the feeders (deviations from the nominal voltage) were found to be frequent for most of the ten feeders, with most of the violations being below the maximum permissible voltage variation of 10%. Voltage violations for all the ten feeders can be found in 7,639 hours out of the 8,760 hours (87.20%) in 2018. The average distribution losses of all ten feeders of Erode substation are at 7.38%.

Introducing solar energy showed significant improvements in the voltage profile and a reduction in voltage violations for all solar energy penetration levels. For the Utility Category, the deployment of solar energy saw the voltage deviations reduce from 87.20% in a Business-As-Usual (BAU) scenario to 8.80% under a 100% solar energy penetration scenario. For the Consumer Category, with the introduction of solar energy and storage systems, the voltage profile changes from lower voltage ranges to upper voltage ranges[1].

Distribution losses under Utility Category were found to decrease by up to 40% of solar energy penetration and then increase gradually for the 70% and 100% solar energy penetration levels on account of solar energy surplus flowing beyond the substation. For the Consumer Category solar, distribution losses within the distribution transformer (DT) network increase with solar energy penetration, as more energy is flowing back to the substation compared to the energy flow under BAU. For the Utility Category solar an increase in solar energy penetration up to 40% shows the maximum CoS reduction to TANGEDCO.

[1] *In this study lower voltage range is defined as 0.90-0.98 p.u. and upper voltage range is defined as 1.02-1.06 p.u. The minimum and maximum allowed grid supply voltage for 22 kV, 11 kV and lower voltage levels in Tamil Nadu are 0.90 p.u. and 1.06 p.u. respectively (TNERC, 2013).*

On the other hand, for Consumer Category solar energy penetration levels, net revenue increases with increase in solar energy penetration and it is the highest for 100% solar energy penetration, reaching 111.43% (INR Cr 0.05) savings when compared to the BAU scenario (no solar PV systems at consumer's premises).

Introduction of ToD tariffs along with solar energy shows positive technical and financial impacts under both, the Utility Category and the Consumer Category solar. Voltage profile improvements during peak demand hours are significant due to ToD tariffs introduction for both cases. For Utility Category, the voltage violations are reduced from 87.20% to 5.97% with the introduction of ToD tariffs and solar energy. All solar energy penetrations under the Utility Category solar show a reduction in distribution losses compared to the BAU scenarios. In terms of current or hosting capacity, 100% solar energy penetration, with and without the introduction of ToD tariffs, is possible for four out of the ten feeders. However, 100% solar energy penetration becomes feasible in combination with ToD tariffs and energy storage for all feeders.

The introduction of energy storage systems was simulated for the 100% solar penetration scenario only. The energy storage systems were sized to store the surplus solar energy going beyond the substation (in the case of the Utility Category solar) or beyond the DT (in the case of Consumer Category solar). A significant improvement in the voltage profiles can be found, as compared to solar energy penetration levels without storage. Distribution losses are reduced significantly. This study concludes that 100% solar can be accommodated without exceeding the feeder's current capacity and that substantial financial savings are estimated for TANGEDCO on a 25 years basis: 94.87% and 105.42% on two feeders (Karungalpalayam Feeder and Market Feeder) for the Utility Category solar and 93.82% for the Consumer Category solar under DT26 when compared to the net revenue as per BAU scenario.

UTILITY CATEGORY

	40%-100% SP	SP + ToD	SP + ToD + Storage
Voltage Violations	Lower limit violations decreases significantly and upper limit violations increases slightly with increase in penetration	Slight improvement in voltage during peak hours	Voltages are mostly within upper and lower acceptable limits
Distribution Losses	Up to 40% solar penetration, distribution losses are less compared to the BAU	Slightly reduced with ToD	Significantly reduced
22 kV Feeder Capacity Violation	Violation can be found after 40% solar penetration	No significant improvements due to ToD	Feeders are able to take 100% solar penetration with no violations
Savings Compared to BAU	Savings are the highest under 40% solar penetration	Small improvement in savings due to ToD	Significant savings can be found in the long term

CONSUMER CATEGORY

	40%-100% SP	SP + ToD	SP + ToD + Storage
Voltage Violations	Up to 40% solar penetration, there are no voltage violations. There are few upper limit violations with increase in penetration	Violations slightly reduced with ToD	Voltages are within upper and lower acceptable limits
Distribution Losses	Distribution losses increase with solar penetration	Slightly reduced with ToD	Significantly reduced
LT Line Current Carrying Capacity	Up to 70% solar penetration, there are no violations	No significant improvements due to ToD	LT lines are able to take 100% solar penetration with no violation
Savings Compared to BAU	Savings increase with solar penetration level	Small improvement in savings due to ToD	Significant savings can be found in the long term

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GLOSSARY OF TERMS

Active Power (Or Real Power): Useful power supplied to consumers, which is actually consumed. Measured in kW.

Average Billing Rate (AvBR): The average monthly bill paid by each consumer, independent of Category. It is the total revenue divided by the total units supplied.

Advanced Solar Inverter: It has: i) the ability to receive operational instructions from a centralized station ii) advanced communication capabilities iii) can make autonomous decisions to improve grid stability iv) support power quality v) active and reactive power management v) provide ancillary services (NREL, 2014).

BAU (Business-as-Usual): A scenario build based on the current situation, where no changes are implemented. Usually, new scenarios are developed and compared to the BAU scenarios and assess how effective are the new scenarios.

Consumer Category Solar: As per Tamil Nadu Solar Policy 2019 (TEDA, 2019), Consumer Category solar energy systems are solar energy systems where the primary objective is self-consumption of solar energy, and export of surplus energy to the grid.

Cost of Supply - CoS (per unit): Price paid by the utility company to supply one unit of energy to the consumers.

Cost of Supply - CoS (total): The total amount paid by the utility to supply energy to all consumers within a particular area.

Distribution Losses: Energy dissipated in the wires, conductors, transformers, and other equipment, and also magnetic losses on the transformers. It is calculated by I2 x R, where I is electrical current (A) and R is resistance (Ω).

Distribution Network: Specifies a boundary in which energy is supplied within the same voltage level.

Distribution Transformer (DT): In power distribution systems, it is the device responsible for stepping down the voltage, to deliver power for low voltage distribution networks.

Energy Balance: It relates input energy and output, involving all losses, transformation and conversions within a given system.

Feeder: Electrical power line responsible for delivering power from a substation to distribution transformers.

Feed-in Solar Energy: Solar energy that is supplied to feeders or the distribution network.

Grid Supply: Energy supplied from centralized generation, usually coal-based, that is subject to transmission and distribution losses.

Levelized Cost of Energy (LCOE): Defines the cost of an unit of electricity produced over the lifetime of a plant or generator

PV (photovoltaic): Refers to solar photovoltaic for electricity production.

Reactive Power: It is the out of phase power, resulting from inductive and capacitive loads. It is measured in KVAr.

Solar Energy Absorbed: Locally produced solar energy absorbed in the distribution network.

Solar Energy Export: Locally produced solar energy exported beyond the substation. It is subject to additional transmissions or distribution losses.

Solar Energy Self-Consumption: Amount of solar energy that is consumed by Consumer Category before being fed-in to the distribution network.

Solar Penetration (%): Amount of solar energy that is equal to a given percentage of the total energy consumption of consumers or feeders.

Solar Plus Storage: Solar energy that, after self-consumption, or after the supplying the required demand, is stored in storage systems.

TANGEDCO: Tamil Nadu Generation and Distribution Corporation Limited.

Time-of-the-day (ToD) Tariffs: A tariff structure where electricity have different times over the day. Usually peak times have higher prices and off-peak periods have lower prices.

TNERC: Tamil Nadu Electricity Regulatory Commission.

Utility Category Solar: As per Tamil Nadu Solar Policy 2019, Utility Category solar energy systems are solar energy systems where the primary objective is the electricity sales to a distribution licensee, third party or self-consumption at a remote location (wheeling).

1. INTRODUCTION

1.1. India's Solar Ambitions | 100 GW of Solar by 2022

India has set ambitious renewable energy (RE) targets of 175 GW by 2022. Of this target, 100 GW is to be contributed by solar energy, 60 GW by wind energy, 10 GW from bio-power and 5 GW from small hydro-power. 40% of India's solar energy target is envisioned to be met from rooftop solar, a clear indication of the recognition of distributed renewable energy generation (DREG) (MNRE, 2020). In addition to its renewable energy targets, India aims to base 40% of its total installed power generation capacity on non-fossil fuel resources by 2030.

As of January 2020, India had an installed RE capacity of 86,321 MW, which represents 23% of the total installed capacity (Central Electricity Authority, 2020). Renewable energy generation grew at 9.46% in one year (2019-2020), in contrast to the growth in conventional generation of 2.01%. In January 2020, RE contributed 10.33 BU (Billion Units) or 9.12% of the total electricity generation (Ministry of Power, 2020).

In 2019, the Ministry for New and Renewable Energy (MNRE) launched Phase 2 of its Domestic Rooftop Solar Program, with an overall solar energy target of 40,000 MW by 2022. The KUSUM scheme launched in 2019 by MNRE aims to promote the deployment of distributed solar in agriculture. KUSUM has 3 components. Component A aims at introducing ground mounted distributed solar energy in the solar capacity range of 500 kW to 2 MW. It has a cumulative target of 10,000 MW by 2022. Component B targets the installation of 17.5 lakh stand-alone solar pumps, while component C aims at the solarisation of 10 lakh grid connected pumps with solar energy capacities of up to 11 kW. (MNRE, 2020).

The Tamil Nadu Solar Energy Policy 2019 set a solar energy target of 9,000 MW by 2023. 60% of this target is allocated to the Utility Category solar and 40% of the target is to be met by the Consumer Category solar (behind-the-meter solar) (TEDA, 2019). As of December 2019, Tamil Nadu has an aggregated installed capacity of Consumer Category[2] solar of 464 MW (12.80% of the total Consumer Category solar target) (Bridge to India, 2019). As of January 2020, solar energy alone, with 3,974 MW installed capacity, represents 12% of the total installed capacity in the State (TEDA, 2020). As of March 2020, the share of renewable energy represents 48% of total installed capacity.

While the recent Tamil Nadu Solar Energy Policy 2019 (TEDA, 2019) provisioned for gross feed-in tariffs for the Utility Category solar at all grid voltage levels in order to encourage distributed generation, the Tamil Nadu Electricity Regulatory Commission (TNERC) has not yet determined solar PV capacity related feed-in tariffs. The Tamil Nadu Solar Energy Policy 2019 introduced a net feed-in mechanism for Consumer Category solar energy. However, HT consumers were excluded from the net feed-in mechanism, due to the perception that this will negatively impact TANGEDCO's tariff revenues. There are also a series of technical reservations about the solar hosting capacity of existing feeders, as well the possible impact of solar on the distribution network's voltage stability and power quality: Will the existing distribution network be able to absorb the locally generated solar energy? What is the technical and commercial optimum solar capacity for each feeder? How does one deal with the intermittency of solar energy generation? Does the distribution network require upgrades of transformer, lines, and capacitor banks? Can distributed solar energy reduce TANGEDCO's CoS? Are large solar power plants or small rooftop solar plants more beneficial to the utility?

This report presents a detailed evidence-based analysis of a selected substation in Erode District, Tamil Nadu, and explores the technical and commercial impacts of different solar PV penetration levels on the distribution network. The main objective of this report is to assess the benefits and challenges of integrating high levels of distributed solar generation at the distribution network level. This report provides evidence which shows that achieving high solar penetration levels up to 70% and 100% is technically possible and financially attractive. This report is targeted at utility companies, grid operators, policy makers and regulators. It aims to contribute towards an enabling policy and regulatory environment for distributed solar energy generation in Tamil Nadu.

1.2. Challenges of the Power Sector | Gap Between CoS and Revenue

One of the most significant challenges for fast-growing emerging economies is energy production and distribution. Energy plays a crucial role in fueling growing industrial and commercial ambitions. India's per capita electricity consumption has almost doubled since FY 2005-2006 with an average increase of 5.10% per year. In the FY 2018-2019, annual per capita consumption had reached 1,181 kWh (Ministry of Power, 2020). In FY 2019-2020 India's electricity consumption stands at 1,144,579 MU (Million Units) and is expected to grow at 13% till FY 2021-2022, reaching 1,300,486 MU[3] (Ministry of Power, 2019). The residential sector's electricity consumption for India is expected to increase at 16% by 2021-2022 compared to 2019-2020, being responsible for 34% of the total increase in electricity consumption (Ministry of Power, 2019). The rising residential electricity consumption is largely fueled by increasing residential air-conditioning (RAC) consumption (Kumar, et al., 2018) and change in consumer behavior patterns on account of growing levels disposable income. Commercial and Industrial consumers will be responsible for 10% and 29% of the increase in electricity consumption respectively. As India is still below the global average of 2,674 kWh/person/year, the country's consumption is expected to increase further.

With the recent COVID-19 pandemic, electricity consumption has fallen substantially, especially so for the industrial and commercial sectors. Energy forecasting has become more uncertain. The expected impact is a sharp contraction of the economic growth in India, affecting the energy demand in the upcoming years. Reduction in electricity consumption when compared to the pre-COVID 19 scenario maybe expected in a range from 4% to 16% depending on the forecasting model adopted[4] (TERI, 2020).

Besides keeping up with electricity demand, another challenge faced in India is Transmission and Distribution (T&D) losses. In FY 2015-2016 T&D losses were estimated to be at 21.42% (Ministry of Power, 2019), higher than the global average of 8.64%. T&D losses in BRIC countries are much lower: Russia (12.59%), Brazil (16.87%) and South Africa (9.99%). In addition, the high number of unmetered consumers, especially agriculture consumers, makes it difficult for TANGEDCO to quantify the actual technical losses.

As per the latest tariff order (TNREC, 2017) TANGEDCO's T&D losses were 20.17%. For the FY 2018-2019, according to TANGEDCO Financial Department, the average CoS was at INR 8.01 per kWh. Revenue realization was at INR 5.83 per kWh, resulting in a revenue gap of INR 2.18 per kWh supplied. For the FY 2018-19, cumulative revenue gap was INR Cr 17,186.76.

[2] Consumer Category solar is defined as solar energy generation where the primary aim is self-consumption of solar energy, whereas for Utility category solar the primary aim is sales of solar energy to the utility or third parties.

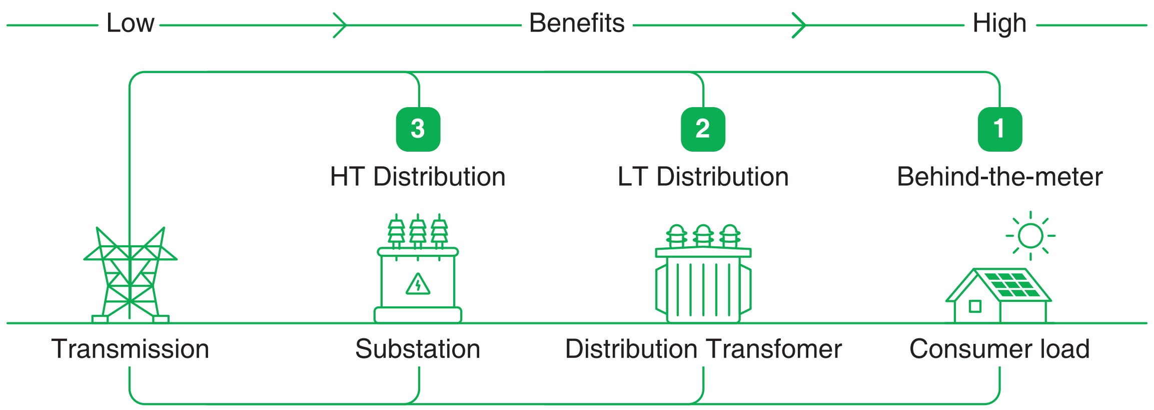
[3] This electricity projection was obtained as per the 19th Electric Power Survey of India. It is important to notice that after the publication of this document, many projections have been carried out showing different figures for the same period of time. The Long Term Electricity Demand Forecast report show figures that range from 1443.5 BU to 1566.0 BU depending on the forecast model. (Central Electricity Authority, 2019)

[4] For the purpose of this report, energy forecasting was done in a pre-COVID 19 scenario.

1.3. Centralized vs. Decentralized Generation | Locational Value of DREG

In recent years decentralized energy systems have gained increasing attention as they have several benefits when compared to centralized systems. For example, decentralized systems contribute to a more resilient system and reliable power supply as Distributed Generation (DG) can reach a larger number of people in a more efficient way, reducing T&D losses, fossil fuels consumption and therefore pollution (Wiser, et al., 2016). DG therefore can contribute to meeting the growing electricity demand in India (IRENA, 2017). Proper siting of DG can reap technical and commercial benefits. For example, locating it near the load centres reduces T&D losses and also defers or avoids infrastructure upgrade costs (Auroville Consulting, 2019). Figure 1 shows the benefits of DG according to the interconnection point.

Figure 1: Benefits of Distributed generation based on location



Source: Adapted from Auroville Consulting (2019).

Some of the benefits of increasing distributed solar energy penetration are:

- Improvement in voltage: In the distribution networks that currently show low voltage levels, which translates into T&D losses, distributed solar energy has the potential to increase the voltage level as energy is injected from the tail-end of the distribution network.
- Reduction of T&D losses: Properly planned addition of decentralized solar generation close to the point of consumption reduces distribution and transmission requirements, hence reducing T&D losses.
- Investment deferral: The necessity to upgrade Distribution Transformers (DT) due to growing energy demand can be reduced by targeted installations of distributed solar energy generation (feeders with day-time peak demand) and distributed storage.
- Renewable Energy Certificates (REC) purchases: Generating solar energy eliminates the need of purchasing RECs for achieving Renewable Purchase Obligation (RPO).
- Contribution to RE Targets: Increasing solar energy penetration contributes to meeting the RE targets.
- Carbon trading: Avoided CO2 emission can be traded on carbon markets, generating extra revenue.
- Job creation potential: Solar energy shows a great job creation potential, especially when considering small scale systems. While utility-scale systems can create up to 6.05 FTE /MW[5], small scale system can create up to 27.32 FTE/MW. (Auroville Consulting, 2019).
- Short gestation periods: Distributed solar energy has short gestation periods (~6 months), whereas the gestation period of conventional power plants could be somewhere between 5 to 6 years or even longer.

[5] *Full-time Equivalent is the ratio of paid hours divided by the total working hours in a year. E.g. an employee that works part-time (4.5 hours per day in a 9-5 schedule) is equal to ½ FTE.*

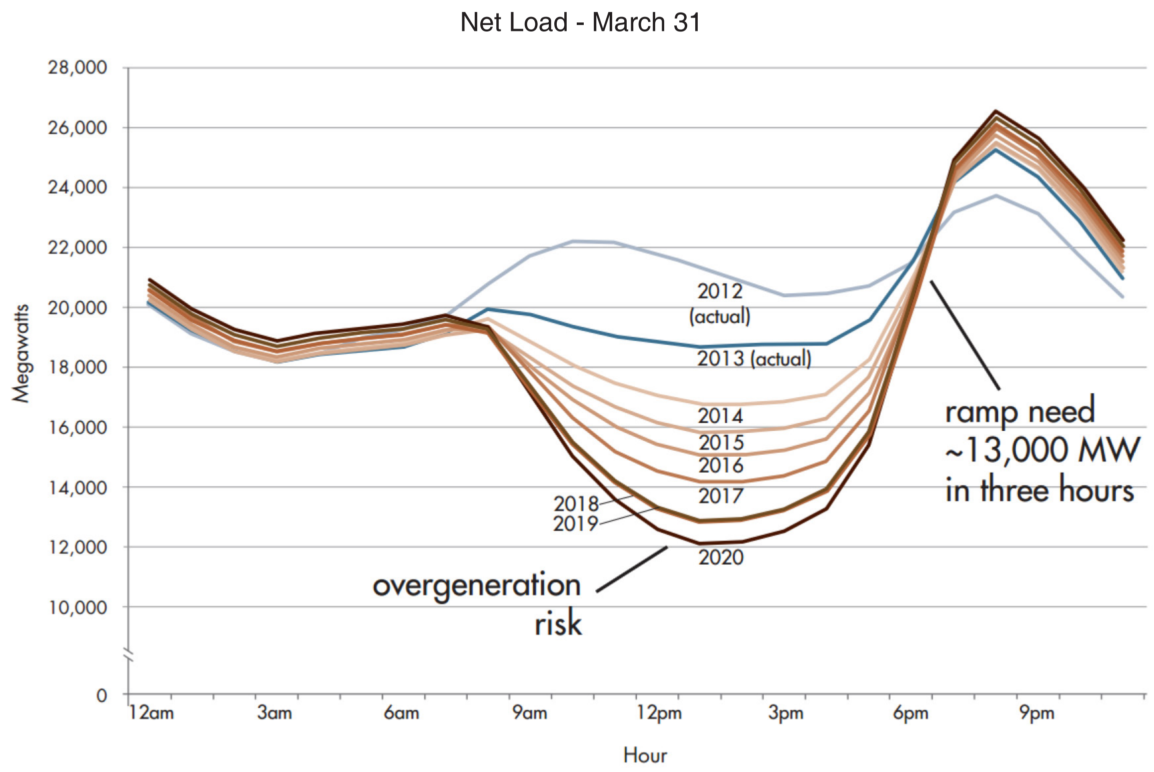
1.4. Achieving High Solar Grid Integration | Flexibility is Key

Despite the benefits of distributed solar energy generation, achieving high solar penetrations presents the utilities with new challenges to be addressed. A few of these challenges are listed below.

Duck Curve

Peak solar energy production usually happens during low demand periods, such as at noon. In high solar penetration levels, the net load, which is the difference between grid energy and solar energy, reaches very low values. When solar production starts to decrease and electricity consumption starts to rise during evening time, a peak of net load may occur, resulting in a phenomenon named the duck curve. For most utilities, addressing the duck curve entails needing to generate a rapid ramping up in thermal energy production in the evening hours, which may come with additional costs and technical challenges. As a result of this phenomenon, utilities often curtail solar energy production as a strategy to deal with the ramping-up requirement (Denholm, et al., 2015). There are several ways to tackle the duck curve, some of which are addressed in the following chapters of this report.

Figure 2: Duck curve example



Source: Adapted from California Independent System Operator (ISO)

Upgrade Costs

Traditional power systems were designed for one-way power flow from centralized generating stations to consumer loads. The deployment of distributed solar generation may affect the smooth operation of the power system by deviating from acceptable bounds, especially for higher solar penetrations. System upgrades may be required at distribution network level in order to maintain voltage stability and to ensure reliability, safety and power quality. The cost incurred for this system upgrade is termed as upgrade costs. Some of the system upgrades include modifying the advanced inverter points to adjust reactive power output, adding new line regulators/capacitors, adjust set points of existing voltage regulators, introducing load tap changer at substation, and reconductoring or replacement of transformers (Horowitz, et al., 2018).

Power Systems Flexibility

Power system flexibility is key for the integration of renewable energy. Power system flexibility is provided from different generation sources, demand response or energy storage technologies. Lack of power system flexibility can bring up operational costs, due to increased ramping-up and startup costs (Chen, et al., 2019). Due to its intermittent nature, grid integration of RE requires more sophisticated methods of generation and demand forecasting.

Demand Side Management

Demand Side Management (DSM) aims to change consumer behavior. ToD tariffs incentivize consumers to shift their loads from peak to off peak hours therefore improving the system load factor (PriceWaterhouseCoopers, 2010).

Storage Systems

Intermittency poses a challenge when scaling up RE integration. Solar energy generation is not available during non-sunshine hours, and it does not meet morning and evening peak electricity demand. With high solar penetration levels, benefits of renewable energy are reduced due to increase in wear-and-tear costs from thermal sources on account of higher ramping requirements (Lew, et al., 2013). One way to address this particular challenge is through Energy Storage Systems. Battery prices have fallen dramatically over the last decade and lower cost of energy storage increases the feasibility of high RE penetration. According to Bloomberg New Energy Finance (BNEF, 2019), Li-Ion battery cell prices have fallen from USD 1,100 per kWh to USD 156 per kWh and are expected to reach USD 100 per kWh by 2023. Some benefits and advantages of storage systems are peak shaving, load levelling, load following, frequency regulation, reliability improvement, reserve application, loss minimization and T&D upgrade investment deferral (Sufyan, et al., 2019).

2. METHODOLOGY | SIMULATING HIGH SOLAR ENERGY PENETRATION

This report presents the technical and commercial impact of various solar energy penetration levels on grid operation and on TANGEDCO's finances. It also compares the potential benefits of Utility Category solar and Consumer Category solar. Additionally, the benefits of introduction of ToD tariffs and distributed energy storage are simulated. The technical part of the feasibility analysis includes determining the feeder's solar hosting capacities, total distribution losses and feeder level voltage violations, while the economic feasibility analysis estimates potential financial savings for TANGEDCO on account of reduction of CoS. The steps taken for the analysis are outlined below:

Step 1: Establish Business as Usual (BAU) Scenario

BAU scenario is defined as the current scenario, without any interventions. It is built on a one year data sample that obtained from the logbooks (hard copies) from Erode substation. For this report, the BAU scenario is used as a reference to compare improvements and benefits of proposed interventions.

Step 2: Simulate Technical Impact of Different Solar Penetration Levels

Solar energy penetrations simulated are: 40% solar penetration, 70% solar penetration, 100% solar penetration. For the Utility-Category solar simulation it is assumed that the solar generators are located near the main load centres. All loads on a feeder were consolidated to a single load at the end of the feeder line.

Step 3: Introduce ToD Tariffs

ToD tariffs were introduced in order to assess their technical and commercial impacts. The adoption of ToD tariffs aims to shift some loads from the evening and morning peak demand hours, to time periods where solar energy generation occurs, in order to maximize solar energy consumption within the distribution network. More details can be found in Appendix E – Time-of-the-day tariffs.

Step 4: Introduce Energy Storage

The impacts on hosting capacity and voltage of the 100% solar energy penetration scenario in combination with ToD tariffs and solar energy storage capacity (generic model was assumed), is simulated. Energy storage capacity is sized at 100% of excess solar energy.

Step 5: Technical Analysis

The main concern is to look at possible voltage violations, either below or above the permissible limit as per Tamil Nadu Electricity Distribution Standards of Performance Regulations (TNERC, 2013) for all simulated solar penetration levels. Another aspect analysed is the distribution losses and current carrying capacity violations on all feeders.

Step 6: Estimate Commercial Impact on TANGEDCO

For the financial analysis the focus is on reducing the average CoS, within and beyond the substation distribution network, and its impact on net gains or losses for TANGEDCO. Savings are compared to the BAU scenario.

The technical simulations were performed using OpenDSS software and python interface. The commercial impact analysis was done from TANGEDCO's perspective only. A commercial impact analysis for generators or consumers goes beyond the scope of this report. The analysis for the Consumer Category solar energy generation (behind-the-meter) followed the same methodological steps as outlined above. The difference is that unlike for the Utility Category solar, where ten feeders were analysed, a single DT and its connected Low Voltages (LV) loads were taken up for the Consumer Category solar analysis. This is due to limitations in available data from other LV distribution networks, as DT metering has only recently started to be implemented by TANGEDCO.

For the Purpose of this Report's Methodology:

Tariff Slab Change is not Considered
Tariff slab change is not considered. Certain consumer categories (for example domestic) in Tamil Nadu have a slab based tariff system, in which the tariff typically increases with consumption. After the installation of a Consumer Category solar energy system, a consumer may move from a higher to a lower tariff slab on account of behind-the-meter solar energy consumption. For simplicity, no tariff slab change for domestic consumers is considered in this report for the financial impact analysis.

Demand Charges are Included in the AvBR Rate
For the commercial analysis, an AvBR including demand/fixed charges was used. Therefore the possible impact of reduced demand charges on account of Consumer Category solar may not be adequately reflected in the results.

Growth in Energy Consumption is not Considered
Most of the analysis was performed over the course of one year. The exception to this is the 100% solar energy penetration scenario with ToD tariffs and energy storage, for which a 25 years' time series has been taken. However no growth in energy consumption has been assumed for this scenario.

Possible Distribution Network Upgrade Costs are not Considered
High integration of distributed solar may require TANGEDCO to invest into voltage regulators, protective devices and (DT) upgrades. Such costs are not taken into consideration for the purpose of this report, as it focuses solely on CoS and net revenue gains to TANGEDCO.

Ownership of Solar PV plants is not Considered
Levelized Cost of Energy (LCOE) values for solar energy generation were used for the financial impact assessment irrespective of the implementation and ownership model of the solar PV plant.

No Diurnal Price Variation on CoS is not Considered
Diurnal price variations on CoS could not be considered in this report as such data is not available in the public domain.

TANGEDCO's Current Power Purchase Agreements and Electricity Sourcing Strategy is not Considered
The technical and commercial impacts of scaling up the solarization of feeder and substations on TANGEDCO are not considered. The deployment of Distributed Solar Energy Generation may affect TANGEDCO's AvBR and Cos. TANGEDCO's Power Purchase Agreements with current suppliers as well as the costs for ramping up and ramping down requriments of the thermal generation fleet is not within the scope of this paper.

Grid Outages were Removed
Any faults, outages and maintenance work leading to lows and highs in the load curves have not been considered in the analysis.

Reduction or Increase in Transmission Losses are not Considered
In most cases energy exported from the substation to 110 kV line normally results in the reduction of transmission losses. However, in this analysis any reduction or increase in the transmission losses is not considered, as only substation level data is available. For the financial calculations a transmission loss of 8% is assumed.

Transient Analysis is not Considered
As more granular data (i.e. smaller timesteps below 1 hour intervals) was not available, the system transient is not analyzed. Frequency was considered constant for the steady state power flow analysis.

3. ERODE SUBSTATION | LOW VOLTAGE PROFILE ACROSS ALL FEEDERS

Erode Substation is a 110/22kV substation maintained by Tamil Nadu Transmission Corporation Limited (TANTRANSCO), with four transformers (2X25 MVA, 110/22kV and 2X16 MVA, 110/22kV). It comprises ten outgoing distribution feeders of 22kV each. The ten feeders cover a total distance of 96.90 Km. A total of 584 DTs are connected to these ten feeders. All feeders have a maximum power carrying capacity of 10 MW[6]. The total sanctioned load of the feeders is 315 MW. The annual energy distributed to the feeders, metered at substation level, was 340,123.69 MWh in 2018 (Refer to Table 1). Note that the power factor assumed is 0.9 for all the analysis.

The majority of consumers of the Erode substation are domestic, followed by commercial and industrial consumers. Residential consumers account for 69.30% of service connections, while commercial and industrial consumers represent 25.90% and 2.80%, respectively. Other categories account for 2.10% of service connections. In terms of energy consumption, domestic consumers account for 50% of the electricity consumption. Commercial and Industrial consumers account for 32.30% and 14.10% of total electricity consumption (Refer to Table 3).

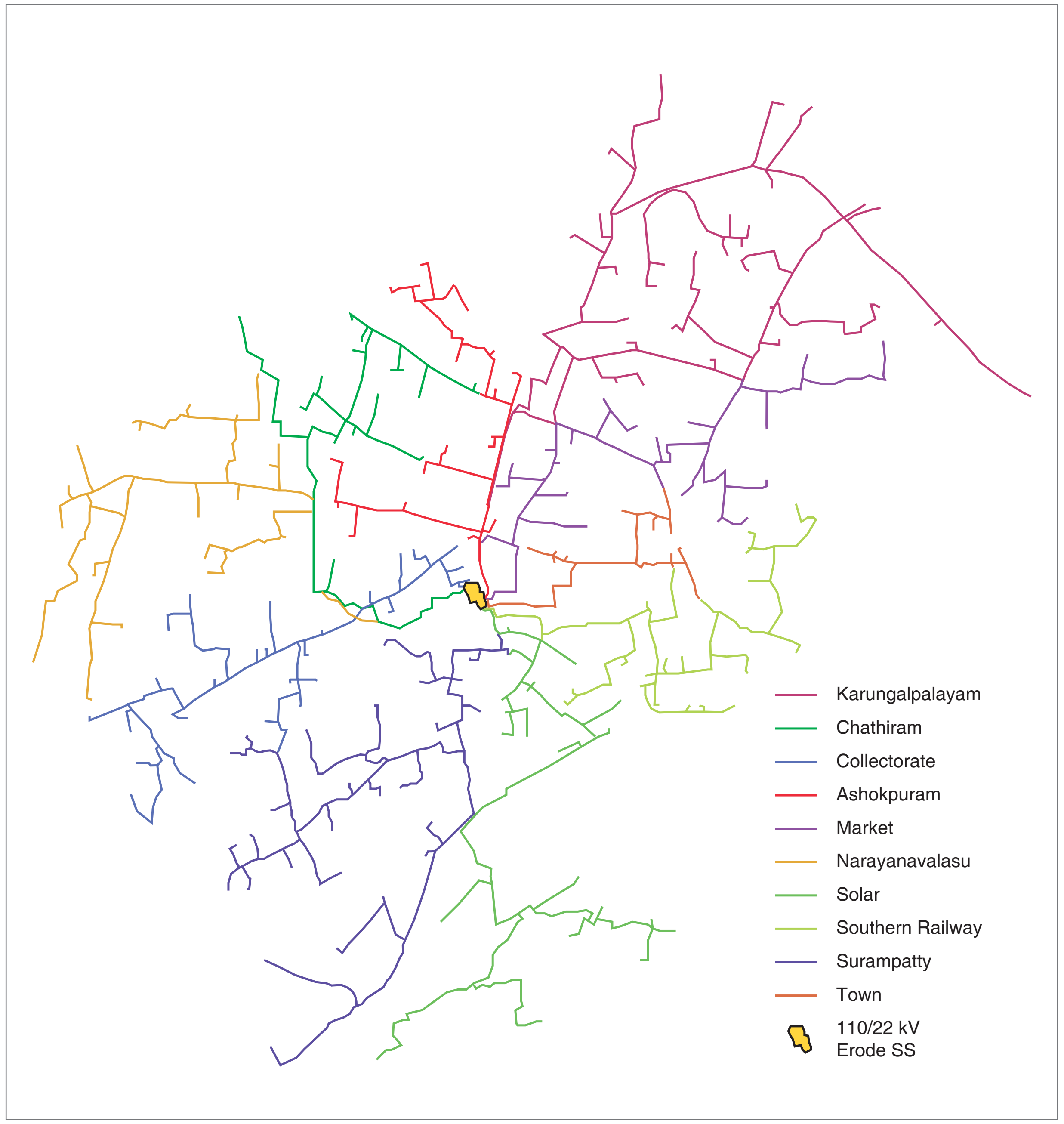
Almost 25% - of the overall electricity consumption occurs between 17:00h and 21:00h, regardless of the month and season of the year Figure 4 depicts the average load curve of all feeders from Erode Substation. It is important to note that load curves for each feeder are not similar, due to different mixes of consumer categories and sanctioned loads. Market Feeder shows the highest annual energy consumption, while Solar Feeder[7] has the lowest annual energy consumption (for load curves of all feeders refer to Appendix B – Load curves). The highest load curve for all the feeders occurs in April and May - the hottest months of the year.

Table 1: Substation General Data and Layout

Substation location	Erode, Tamil Nadu
GIS Coordinates	11°20'15" N, 77°43'00" E
No. of feeders	10
No. of power transformers	4
No. of DTs	584
Power transformer capacity (MVA) and voltage ratings (kV/V)	2x25 MVA,110/22 kV-2 Nos.
	2x16 MVA,110/22 kV-2 Nos.
Distribution line length (km)	93
Annual energy consumption of the SS (MU)	340.12
Estimated distribution losses per feeder	10%

[6] The maximum power capacity = (1.732×22 kV×300 A×0.9 (PF))/1000 ≈10 MW. 300 A is the maximum current carrying capacity of the conductors used on the 22 kV feeders.
[7] Solar Feeder is the proper name given by TANGEDCO to this feeder at Erode Substation. This feeder does not have any solar energy systems connected.

Figure 3: Erode Substation Feeders and GIS DT26 Layout



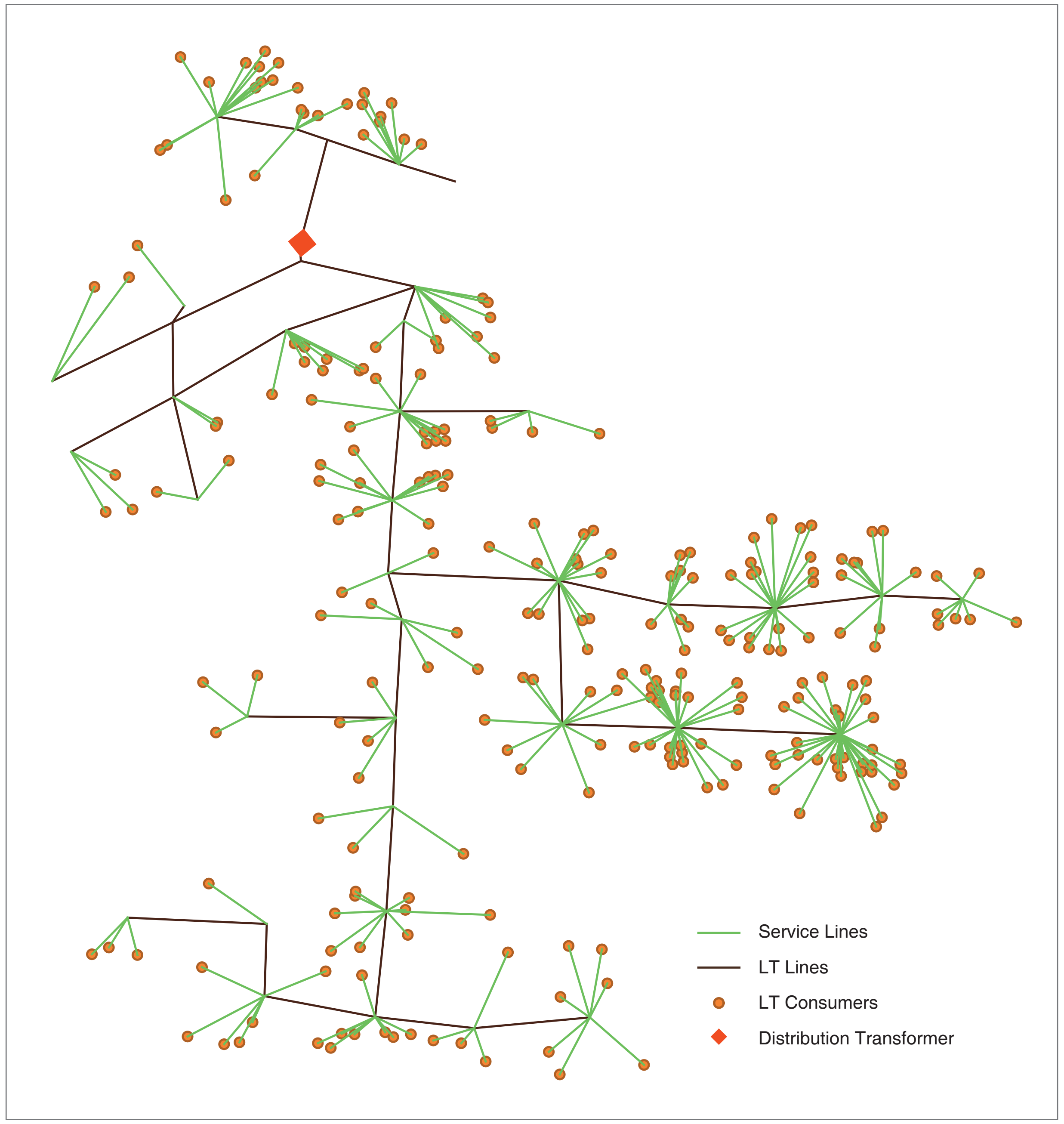


Table 2: Feeders data

Name of Feeder	# of DTs	Length (km)	Sanctioned Load (MW)	Feeders Capacity (MW)	Energy Consumption (MU)
Collectrate Feeder	66	8.89	29.10	10	30,198.08
Chatram Feeder	46	7.62	23.70	10	40,937.48
Narayanavalasu Feeder	87	11.19	51.37	10	50,700.37
Ashokapuram Feeder	78	6.48	44.70	10	49,838.80
Karungalpalayam Feeder	113	18.96	41.60	10	45,552.52
Market Feeder	70	8.87	14.74	10	51,065.43
Erode town Feeder	29	3.57	34.35	10	18,750.66
Southern railway Feeder	51	8.19	37.86	10	25,239.55
Surampatty Feeder	27	13.36	9.70	10	19,374.72
Solar Feeder	17	9.78	27.87	10	8,466.03
Total	**584**	**96.91**	**314.99**	**100**	**340,123.69**

Table 3: Consumers profile

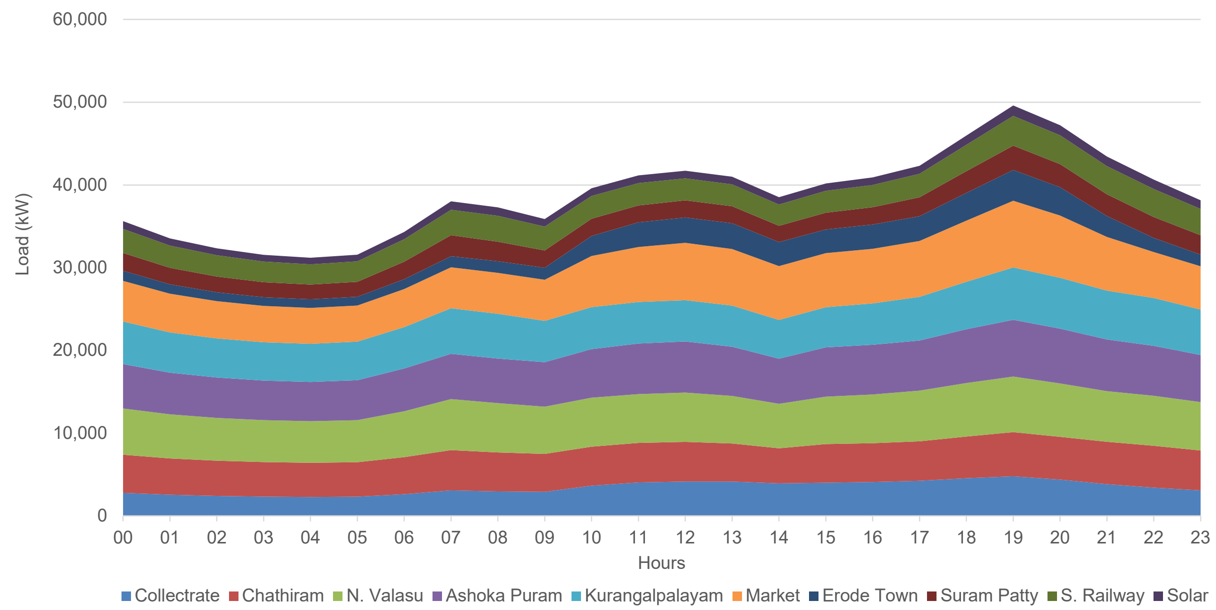
	Domestic		Commercial		Industrial		Others		Total	
Tariff Category	IA		V		IIIA & IIIB		-		-	
Name of Feeder	No.	Load (kW)	No.	Load (kW)	No.	Load (kW)	No.	Load (kW)	No.	Load (kW)
Collectrate Feeder	5,451	14,233	2,229	15,005	213	4,044	248	1,077	8,141	34,359
Chatram Feeder	8,476	15,495	1,849	5,168	618	6,431	185	782	11,128	27,876
Narayanavala-su Feeder	10,290	20,598	1,414	3,975	704	11,687	375	1,606	12,783	37,865
Ashokapuram Feeder	9,337	17,939	3,731	13,754	826	8,760	258	1,178	14,152	41,630
Karungalpa-layam Feeder	15,060	27,448	3,074	8,754	303	6,636	435	1,903	18,872	44,742
Market Feeder	9,990	22,741	7,949	23,194	187	3,722	344	1,717	18,470	51,374
Erode Town Feeder	2,086	4,789	5,373	17,732	39	303	120	939	7,618	23,763
Southern Rail-way Feeder	11,484	20,084	2,096	7,220	72	564	272	1,287	13,924	29,154
Solar Feeder	2,766	5,615	817	3,177	53	582	70	340	3,706	9,714
Surampatty Feeder	3,925	9,114	911	3,693	116	1,613	84	322	5,036	14,742
Total	**78,865**	**158,057**	**29,443**	**101,672**	**3,131**	**44,343**	**2,391**	**11,149**	**113,830**	**315,221**
%	**69.30%**	**50.10%**	**25.90%**	**32.30%**	**2.80%**	**14.10%**	**2.10%**	**3.50%**	**100.00%**	**100.00%**

For the aforementioned Consumer Category solar (behind-the-meter) analysis, a single DT (DT26) connected to the Collectrate Feeder was analysed. DT26 is a 22/0.44 kV transformer with a capacity of 200 MVA and a total connected load of 636.97 kW. DT26 has a total of 254 electrical service connections associated, out of which 170 (67%) are residential, 72 (28%) are commercial and 9 (4%) are industrial. The remaining 1% is dispersed to multiple other consumer categories and street lights. A simple layout of the DT26 and its connected loads is shown in Figure 3. It is important to notice that all loads under DT26 are LT (low tension) loads.

Table 4: DT26 Consumer data

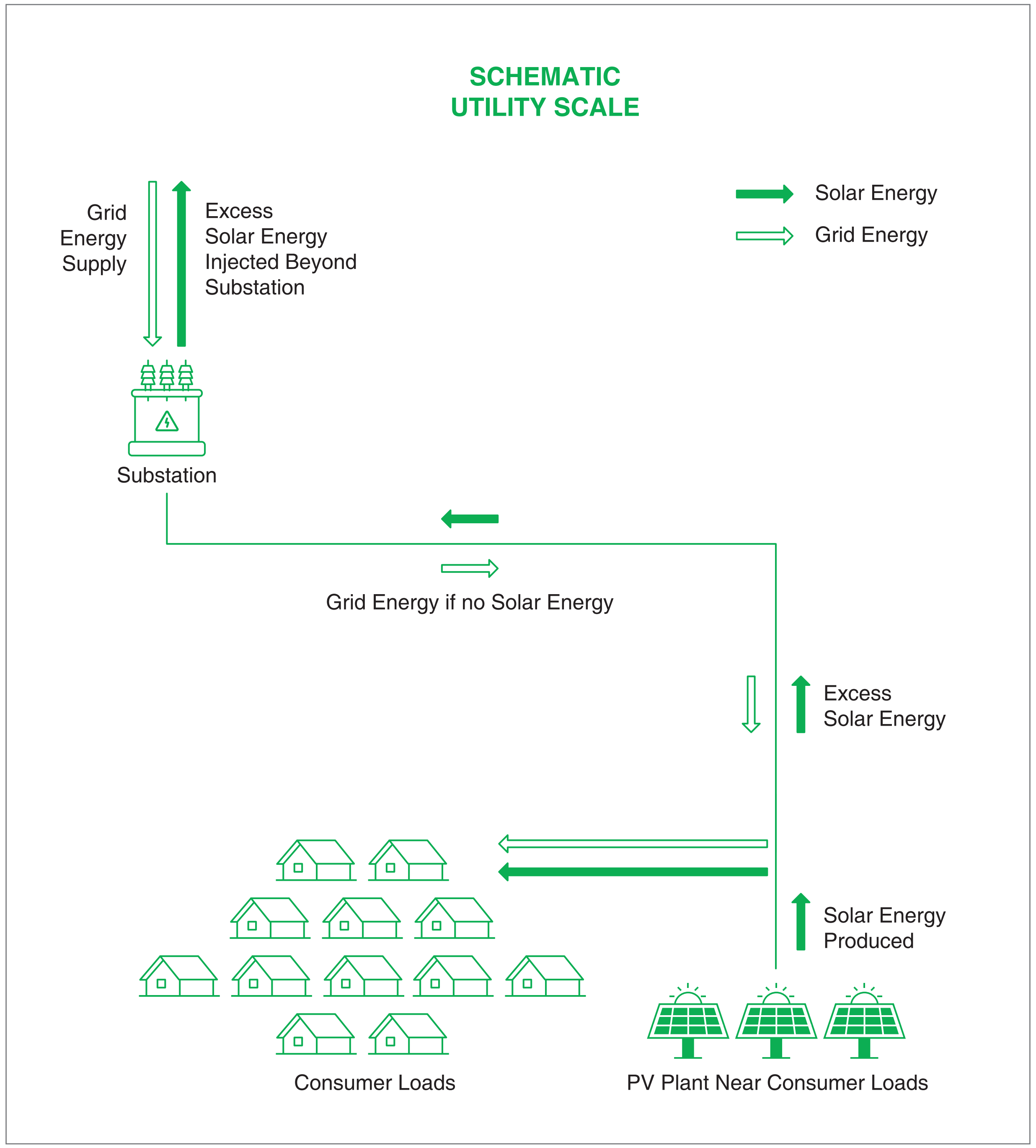
Type of Consumer	Billing Rate (INR)	Number of Connections (#)	Units Consumed (kWh)
Residential	2.18	162	241,931.20
Commercial	9.77	62	245,720.60
Industry	5.11	9	129,379.00
Others	5.91	3	6,360.00
Total	**-**	**236**	**623,390.80**

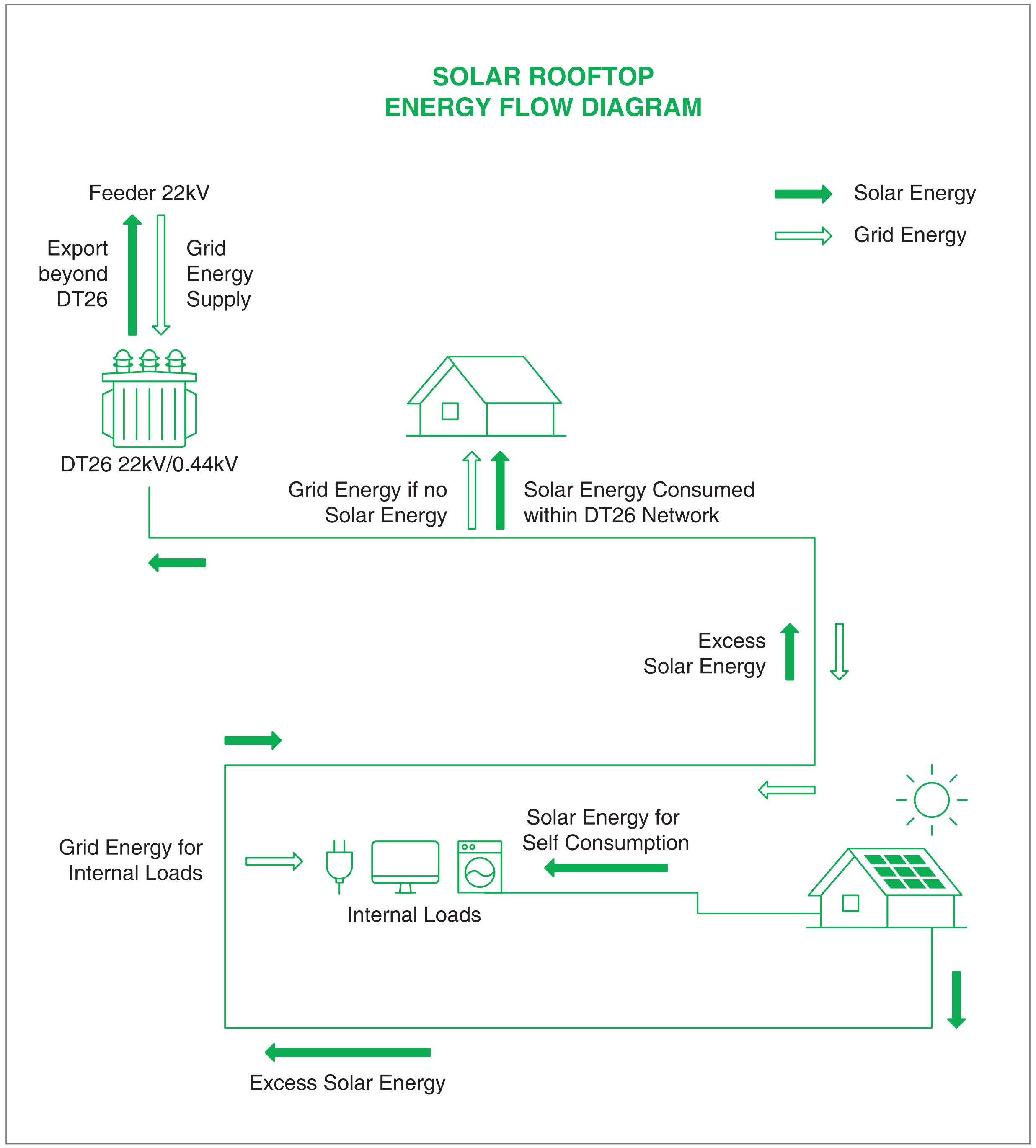
Figure 4: Yearly Average Energy Curve



A schematic diagram depicting the interconnection point the distribution network of the solar energy systems and the consumer loads for both the Utility Category solar and the Consumer Category solar is shown in Figure 5.

Figure 5: Schematic diagram for Utility and Consumer Category





4. SIMULATING IMPACTS ON UTILITY-CATEGORY SOLAR | LEVERAGING EXISTING HT DISTRIBUTION INFRASTRUCTURE

This chapter outlines the techno-commercial simulations performed for the 10 feeders of Erode Substation. Simulation were performed for the BAU scenario, and for Utility Category energy penetrations at 40%, 70% and 100%. Solar energy penetration in this context is defined as the percentage of each feeder's total annual energy consumption as per BAU. In addition to different levels of solar energy penetrations, the introduction of ToD tariffs was simulated. The last section in this chapter explores the impact of introducing energy storage for the 100% solar energy penetration scenario. This is done for two feeders: Karungalpalayam Feeder and Market Feeder.

4.1. Business-as-Usual (BAU) – No Solar

Technical Analysis:
Under Utility Category solar, the feeders are analysed individually over their total extension. The energy consumption and voltage data were collected and analysed at substation level. In 2018, aggregated voltage violations for all feeders, were found 87.20% of the time (7,639 hours out of 8,760 hours) (Refer to Table 5). According to the Amendment on Distribution Performance (TNERC, 2013), voltages should present a maximum variation of 6% above the rated voltage and a maximum variation of 10% below of the rated voltage. It is important to note that all voltage violations identified are below the minimum acceptable limit and not a single instance of a voltage variation above the maximum limit was found in the BAU scenario.

Table 5: Voltage violations under BAU scenario

	Number of Hours	% of Hours in a Year
Low (below 10%)	7,639	87.20%
High (above 6%)	0	0.00%

An illustrative example of voltage violations for the 25th and 26th October 2018 is shown in Figure 6. These days were selected since they showed the highest number of feeders violating the voltage limits. During the 11:00h to 12:00h (25th October 2018), five feeders (Surampatty Feeder, Karungalpalayam Feeder, Narayanavalasu Feeder, Market Feeder, and Ashokapuram Feeder) had voltages lower than the 10% maximum variation. Two feeders in particular, Karungalpalayam and Narayanavalasu Feeders consistently have low voltage in excess of the maximum permitted low voltage deviation throughout the year.

Figure 6: Voltage violation under BAU for 10 feeders during 25th to 26th October 2018

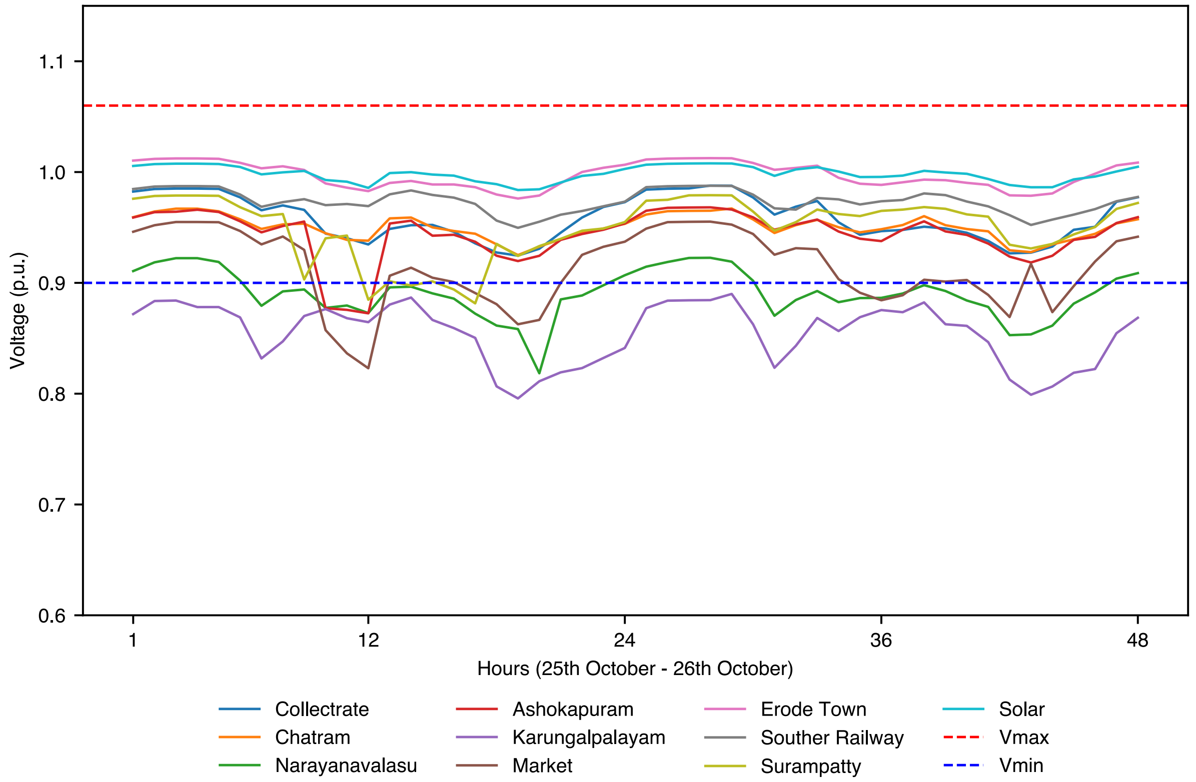
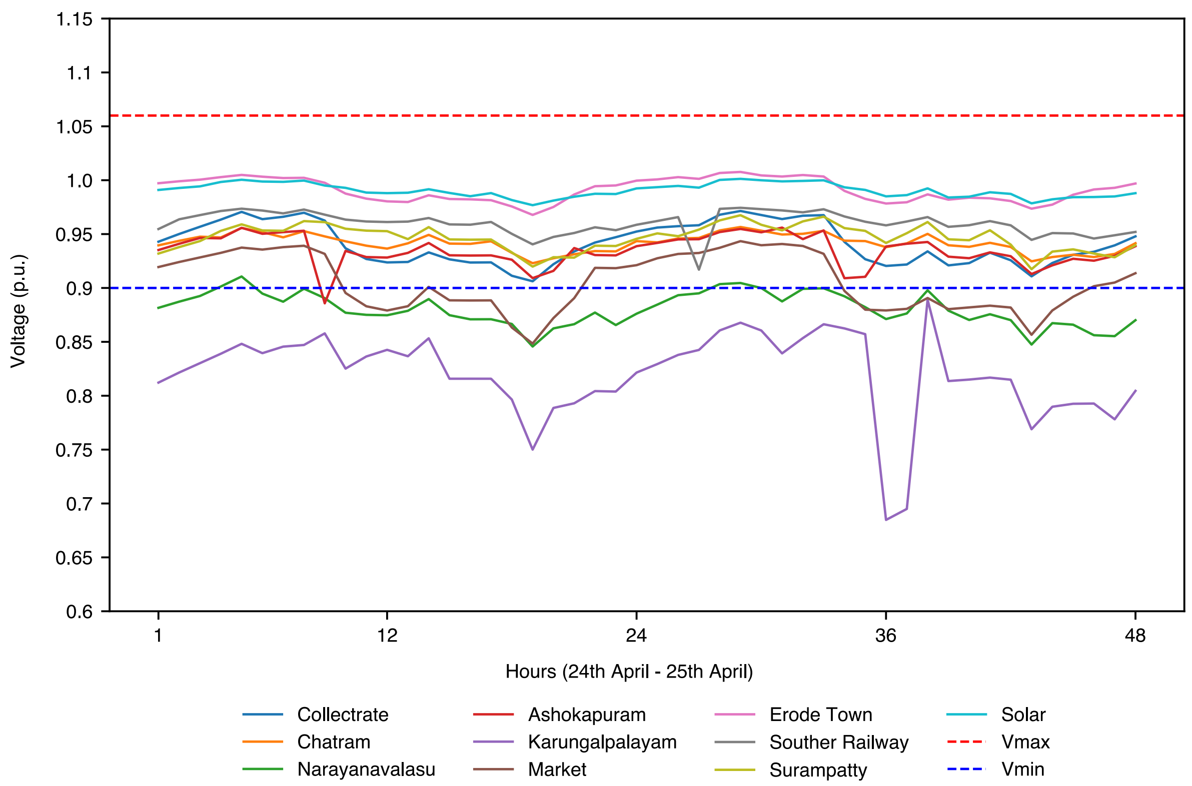


Figure 7 shows each feeder's voltages during the substation's highest peak demand in 2018, recorded on 24th April at 19:00h. Voltage levels for Karungalpalayam, Narayanavalasu, and Market Feeders have voltages which are often below the minimum permitted voltage, while the remaining feeders are within recommended voltage limits. A sudden increase in the demand from 4.90 MW to 8.90 MW in the Karungalpalayam feeder at the 36:00h hour (25th April) results in a voltage dip reaching 0.70 p.u.

Figure 7: Feeder voltage during peak demand of substation



Significant voltage drops may result in an increase of current flow to certain loads, an increase in distribution losses and a shorter life span of appliances and power cables. Higher distribution losses increase the average CoS per unit to TANGEDCO, since more power needs to be purchased or generated to deliver the same amount of energy to the consumer.

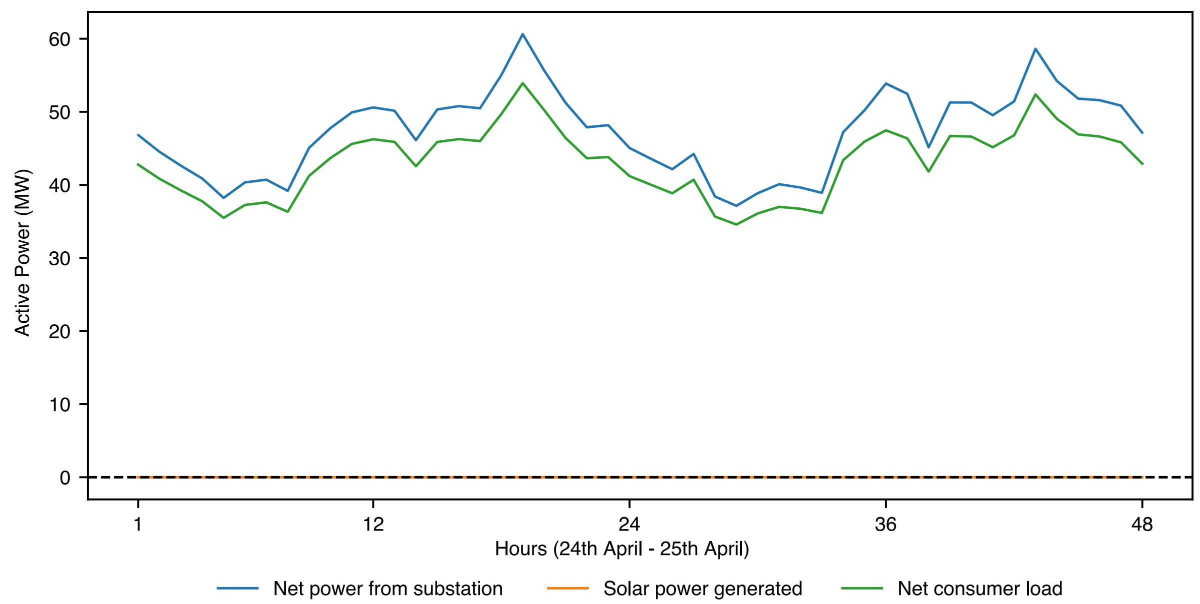
Table 6 shows the net energy output per feeder and their network losses. Network losses are found to be higher for Karungalpalayam Feeder, Narayanavalasu Feeder and Market Feeder primarily due to their comparatively higher connected load and their larger distribution line length.

Table 6: Feeders losses and reactive support

Feeders	Energy Metered At SS Level (MWh)	Losses (MWh)	Losses As Percentage Of Total Energy Supply (%)	Reactive Power Support From Grid (MVArh)
Collectrate Feeder	30,198.08	1,486.06	5.18%	14,836.27
Chatram Feeder	40,937.48	2,220.06	5.73%	20,166.96
Narayanavalasu Feeder	50,700.37	5,054.59	11.07%	25,359.44
Ashokapuram Feeder	49,838.86	2,814.69	5.99%	24,583.28
Karungalpalayam Feeder	45,552.52	7,092.82	18.44%	23,196.59
Market Feeder	51,065.43	4,203.90	8.97%	25,401.43
Erode Town Feeder	18,750.66	263.77	1.43%	9,109.77
Southern Railway Feeder	25,239.55	901.35	3.70%	12,339.07
Solar Feeder	8,466.03	155.17	1.87%	4,082.10
Surampatty Feeder	19,374.72	906.08	4.91%	9,476.79
Total	**340,123.69**	**25,098.50**	**7.38%**	**168,551.70**

Figure 8 depicts the net active power for the BAU case. Here, there is no solar generation and all the consumer demand is met from the substation.

Figure 8: Net Active power – BAU case



Financial Analysis:
In the calendar year 2018 (January to December), TANGEDCO incurred a total loss on electricity supply at Erode Substation of INR Cr 84.48 or 46.00% of revenue collected for the energy supplied to the feeders. The primary reason for this loss is the fact that the Average CoS is higher than the AvBR, but the financial losses in the case of Erode Substation are accentuated by higher distribution losses on many of the ten feeders (Refer to Table 7).

Table 7: Financial analysis BAU scenario – Utility Category

	Value
Grid Energy Metered @ SS Level (MU)	340.12
Consumer Loads (MU)	315.03
CoS Grid Energy per unit (INR per kWh)	7.88
Total CoS Within Distribution Network (INR Cr)	268.14
Average Billing Rate (INR per kWh)	5.83
Revenue From Electricity Billing (INR Cr)	183.66
Net Revenue (INR Cr)	**(84.48)**
Net Revenue (In %)	**-46.00%**

The BAU scenario can characterized by three main points: (i) low voltages levels i.e. 87.20% of the time voltages are more than 10% below the rated voltage; (ii) high distribution losses, with a total of 7.38% of the total energy supplied by the feeders; and (iii) negative net revenue of INR Cr (84.48), or 46% of all the revenue collected.

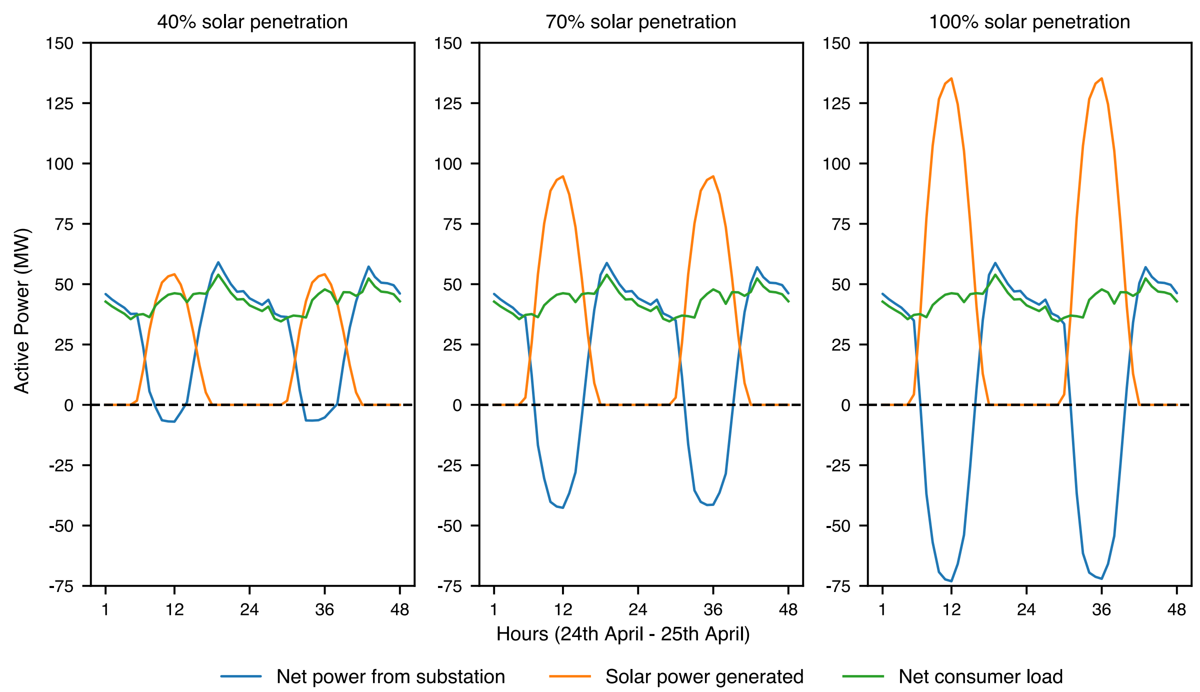
4.2. Solar Penetration | 0% to 100%

This section analyses multiple solar energy penetration levels of 40%, 70% and 100% for each of the ten feeders from Erode Substation. The aforementioned solar penetration levels were determined according to the energy consumption of each feeder; the details and methodology of which can be found in Appendix C – Solar and storage systems. First, a technical analysis is presented, followed by an analysis of the financial impact on account of TANGEDCO introducing solar energy.

Technical Analysis:

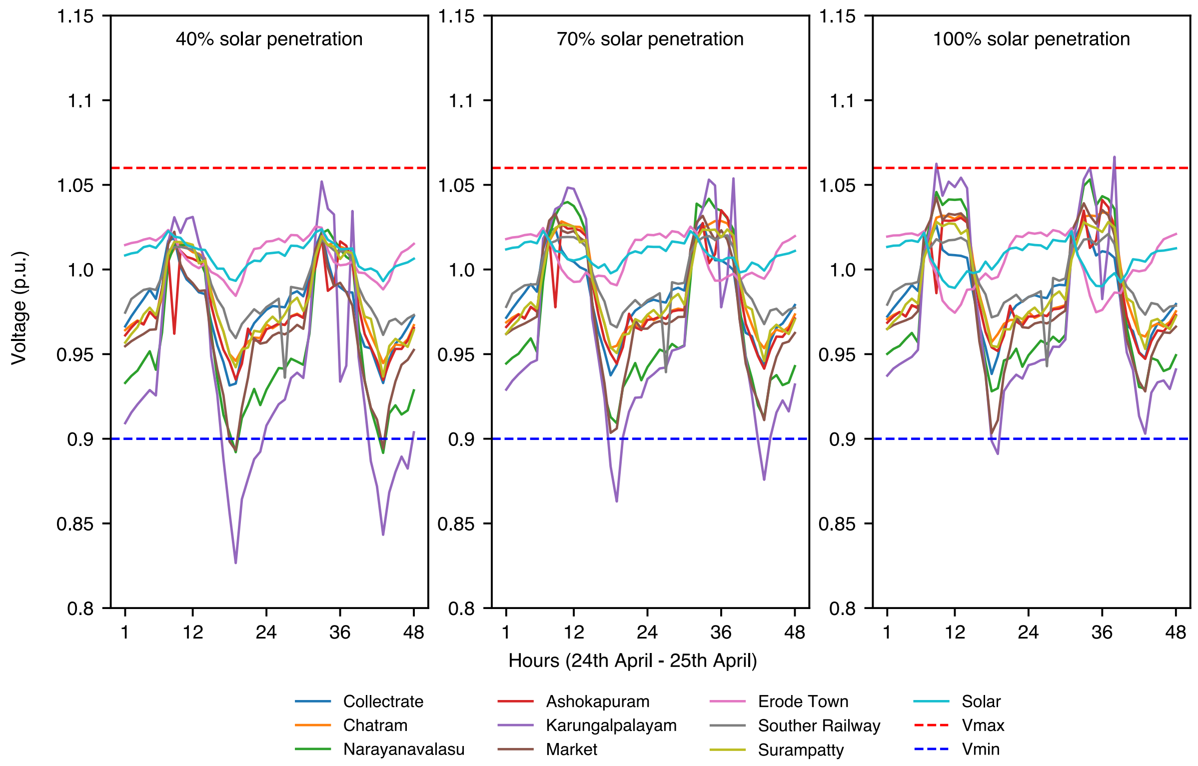
Active power
The results for all three solar penetration levels show that during peak solar generation hours (around noon), all electricity consumption is met from solar energy generated by the simulated solar penetrations. In all three solar penetration levels there is surplus solar energy that flows beyond the Erode substation, the quantum of which intensifies with the increase in solar capacity (Refer to Figure 9). For the 40% penetration scenario the surplus solar energy flowing beyond the substation occurs from 9:00h to 14:00h, for the 70% scenario it occurs from 8:00h to 15:00h and for the 100% scenario it occurs from 8:00h to 16:00h.

Figure 9: Net active power for different solar penetration during peak demand hour of the substation



Voltage
Voltage profiles improve with an increase in solar energy penetration (Refer to Figure 10). The large voltage dip recorded on 25th April 2018 (see Figure 6) is, with all three solar energy penetration levels, reduced to acceptable limits. This is primarily on account of the reactive power support provided from the advanced solar inverters and due to the injection of active power (solar energy) at the tail-end of the distribution network. During most of the hours in the calendar year 2018 voltage fluctuations are within the acceptable limit and voltage violations reduce drastically with each increase in solar energy penetration. It reduces from 87.20% of the time under BAU to 8.80% of the time under 100% solar penetration (Refer to Table 8). The deployment of advanced inverters prevents upper limit voltage violations. Normally, inverters operate in the 3rd quadrant (active energy export, capacitive-reactive energy export). When voltage exceeds a preset upper limit, inverters operate in the 2nd quadrant (active energy export, inductive-reactive energy import) thereby absorbing reactive power from the electricity network and therefore reducing voltage (Refer to Table 8).

Figure 10: Voltages of the 10 feeders for different solar penetration during peak demand hour of the substation



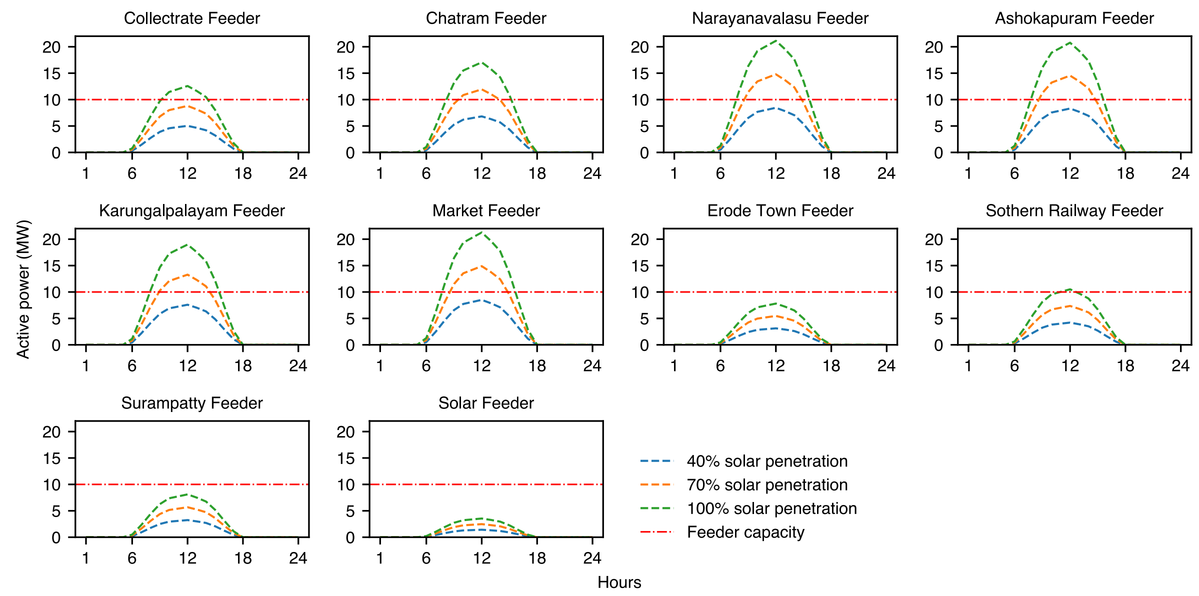
Distribution losses

It is found that with increase in solar penetration to a certain point (about 40%), losses decrease as most of the energy consumption is met from local solar generation (Refer to Table 8). With 100% solar energy penetration, an increase in distribution losses can be observed due to higher energy flowing back to the substation from solar generators compared to the energy flowing from substation to the loads under the BAU scenario. One of the loss reduction strategies that can address this is the introduction of energy storage systems, as explained in section 4.4. The reduction in distribution losses can be linked to the improvement in voltage levels for 40% and 70% solar penetration levels, however not applicable to 100% solar penetration level, due to high levels of energy flowing back to the substation.

Feeder capacity

The maximum power carrying capacity of each of the 22 kV feeders is around 10 MW. Since solar penetration was designed according to each feeder's energy consumption, the amount of solar PV capacity connected to each feeder differs. Feeders are able to hold different penetration levels depending on their energy consumption, as maximum power carrying capacity is the same for all feeders. Up to 40% solar energy penetration, all the feeders are within the maximum energy capacity. Even under the 100% solar energy penetration scenario, the three feeders (Solar Feeder, Erode town and Surampatty) does not exceed the feeder capacity limit. For Southern Railway Feeder, the peak solar generation is 10.50 MW which is only slightly higher than the maximum power carrying capacity (Refer to Figure 11). With the smart inverters active power control, 100% solar energy penetration is feasible for the Southern Railway Feeder. Thus 100% solar energy penetration is possible for four out of ten Feeders. If energy storage is deployed to absorb the surplus solar energy, the power flow will be within the maximum capacity limit for all feeders and for all solar energy penetration levels.

Figure 11: Generation curves for different solar energy penetration levels



With an increase of solar energy penetration, energy imported from beyond the Erode Substation gradually decreases on account of higher local solar energy generation. Even with the 100% penetration scenario energy import from beyond the substation is still required, primarily for non-solar generation hours. With higher solar energy penetration levels, the solar energy flowing beyond the Erode Substation increases proportionally (Refer to Figure 12).

Figure 12: Energy Balance - Utility Category

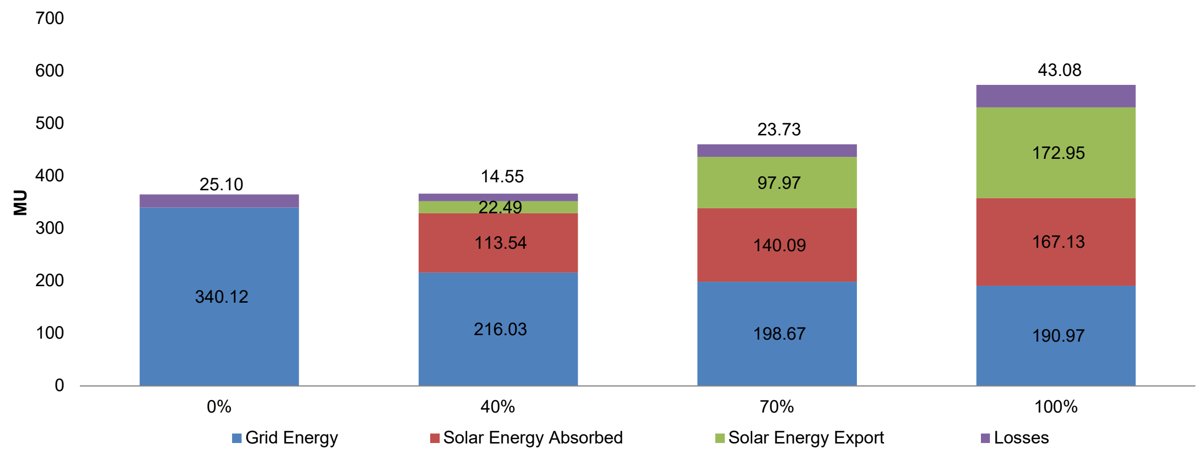


Table 8: Solar penetration analysis - Utility Category

	0% (BAU)	40%	70%	100%
Capacity Installed (MWp)	-	85.88	150.28	214.69
Solar Energy Produced (MU)	-	136.03	238.06	340.08
Grid Energy metered @ SS level (MU)	340.12	216.03	198.67	190.97
Voltage Violations (%)	87.20%	18.10%	8.20%	8.80%
Reactive Power Support (KVArh)	100.00%	71.90%	89.80%	114.00%
Distribution Losses[8](%)	7.38%	4.62%	7.53%	13.68%
Total CoS (INR Cr)	268.14	225.90	261.15	307.48
Revenue (INR Cr)	183.66	189.49	209.65	231.68
Net Revenue (INR Cr)	**(84.48)**	**(36.41)**	**(51.51)**	**(75.80)**
Savings over BAU Net Revenue[9](%)	**-**	**62.22%**	**62.05%**	**54.14%**

Financial Analysis:
The 40% solar energy penetration level results in net revenue saving to TANGEDCO of 62.22% when compared to the BAU scenario. At this solar energy penetration level, distribution losses are reduced substantially on account of less amount of energy flowing from substation to the loads. A moderate amount of solar energy is exported beyond the substation and therefore requiring transmission. The 70% solar penetration level results in savings to TANGEDCO of 62.05%. Under the 100% solar penetration level savings of 54.14% over BAU is observed. The lower savings when compared to the other solar penetration scenarios are on account of higher distribution losses and a higher volume of solar energy flowing beyond the substation (Refer to Table 8).

Table 9 compares TANGEDCO's CoS per unit of grid energy, solar energy absorbed within the distribution network and solar energy exported beyond the substation. CoS variations between the different scenarios are on account of (i) different voltage drops and therefore of different distribution losses, (ii) different quantum of energy distributed and transmitted and (iii) different costs of energy generation.

The total CoS within distribution network decreases from BAU and remains practically constant under 40% and 70% penetration, it increases again under 100% solar penetration. The average energy CoS to TANGEDCO including distribution and transmission losses of both energy flowing from the substation and solar energy is the lowest under the 40% penetration scenario with, INR 7.69 per kWh, followed the 70% scenario with INR 7.77 per kWh and INR 7.93 per kWh under the 100% penetration scenario (Refer to Table 10).

Table 9: CoS per unit

	0%	40%	70%	100%
CoS Grid Energy per kWh	7.88	7.69	7.77	7.93
CoS Solar Energy within Substation per kWh	-	4.35	4.39	4.47
CoS Solar Energy Beyond Substation per kWh	-	4.59	4.63	4.71

Table 10: Average CoS and revenue gap per unit

	0%	40%	70%	100%
Average CoS per unit	8.51	6.95	7.26	7.74
Revenue Gap per unit	(2.68)	(1.12)	(1.43)	(1.91)

The highest average CoS is found at the BAU scenario, which incurs also in the highest revenue gap. The Utility Category solar penetration at any level will incur in savings to TANGEDCO. Savings over BAU scenario are the highest for the 40% solar penetration level.

[8] Percentage (%) of losses are calculated on total losses divided by total energy supplied by the grid
[9] For calculating the savings compared to the BAU scenario, the amount of energy supplied in the BAU is modified to match the energy supplied in the other scenarios.

4.3. Solar Penetration and ToD tariffs | Shifting Peak Load and Increasing Revenue

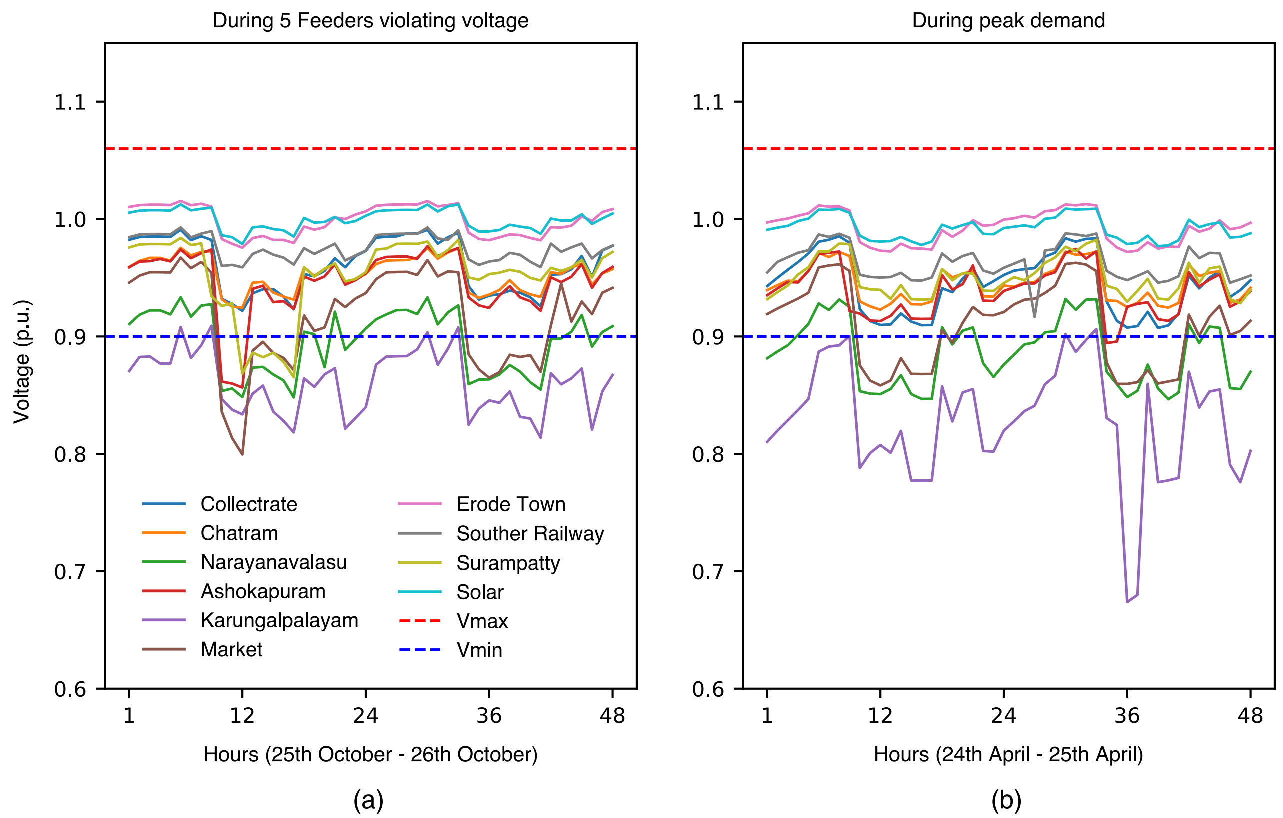
Introducing a higher ToD tariff rate of 20% surcharge for the morning and evening peak hours and a rebate of 5% during off-peak hours (22:00h – 05:00h), results in positive technical and commercial results. A higher electricity tariff rate during peak times (06:00h-09:00h and 18:00h-21:00h) is assumed to have two effects: (i) a shift of 10% of peak energy consumption to the normal hours (10:00h – 17:00h) and (ii) a reduction in electricity consumption to the tune of 10% of total electricity consumed during peak hours (PriceWaterhouseCoopers, 2010). A reduction of 10% of electricity supplied during peak hours translates into a lower revenue loss to TANGEDCO. The higher tariffs during peak hours generate extra revenue and reduce the gap between cost of supply and tariff revenue. More details on ToD tariffs calculations can be found in Appendix E – Time-of-the-day tariffs.

Technical Analysis:

Implementing ToD tariffs with no solar penetration (0%)

Voltage violations observed in five feeders on 25th and 26th October 2018 when ToD tariffs are implemented are presented in Figure 13 (a). With the shifting of loads from peak hours to off-peak hours an improvement in voltage during evening hours can be observed, predominantly from 18:00h to 21:00h. Since a part of the loads has been shifted to normal hours under ToD tariff, a decrease in voltage during normal hours, especially from 12:00h to 16:00h, can be observed. A similar pattern for the voltage profile can be seen on 24th and 25th April 2018, the days on which annual peak demand for the substation occurs (Refer to Figure 13 (b)). Feeders with the most voltage violations are: Karungalpalayam Feeder, Narayanavalasu Feeder and Market Feeder. There is an improvement in voltage compared to the BAU scenario. Under ToD tariffs, aggregated feeders' violations are 6,918 hours, a reduction of 721 hours when compared to the BAU scenario. This corresponds to 78.97% of the time, or an 8.23% reduction.

Figure 13: Feeder voltage for 0% solar penetration plus ToD tariffs during maximum voltage violating feeders

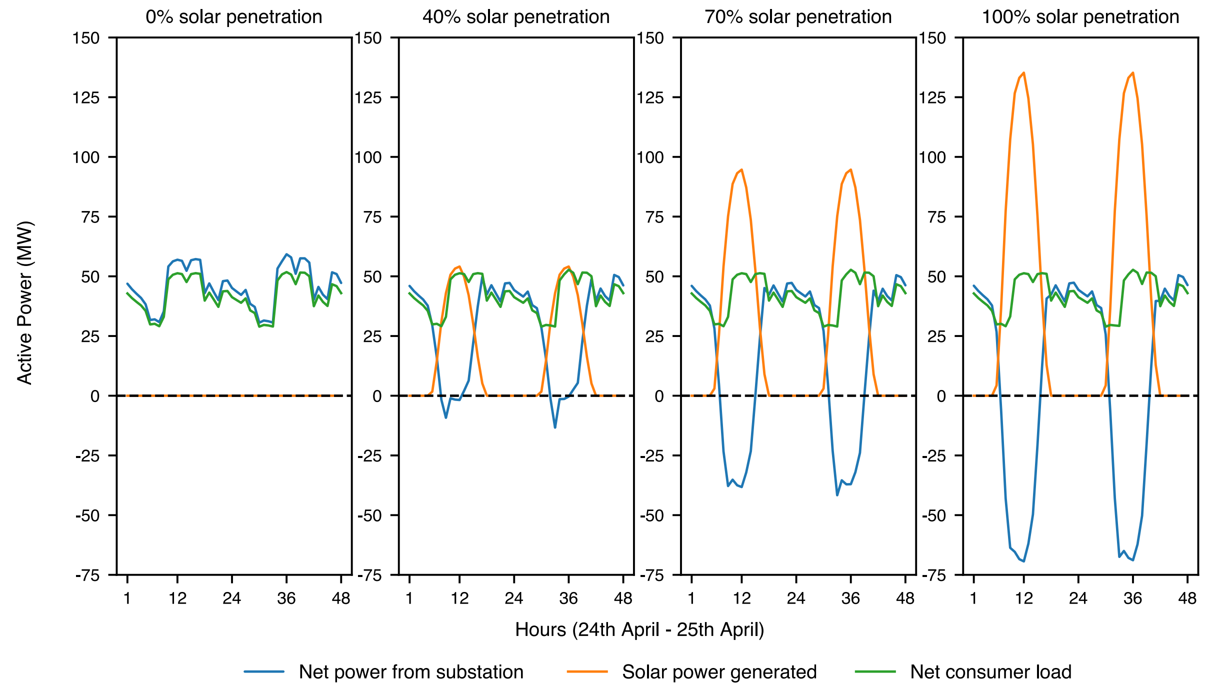


Solar Penetration with ToD tariffs

Active power

Under BAU the annual peak was recorded on 24th April at 19:00h. With the introduction of ToD tariffs this peak shows a clear reduction, with peak hours shifting from evening hours to afternoon hours. For the solar energy penetration levels, introducing ToD tariffs shows an increase of solar energy absorbed within the distribution network during solar hours, especially for the 40% penetration scenario. This results in less solar energy exported beyond the substation during peak solar generation hours (Refer to Figure 14).

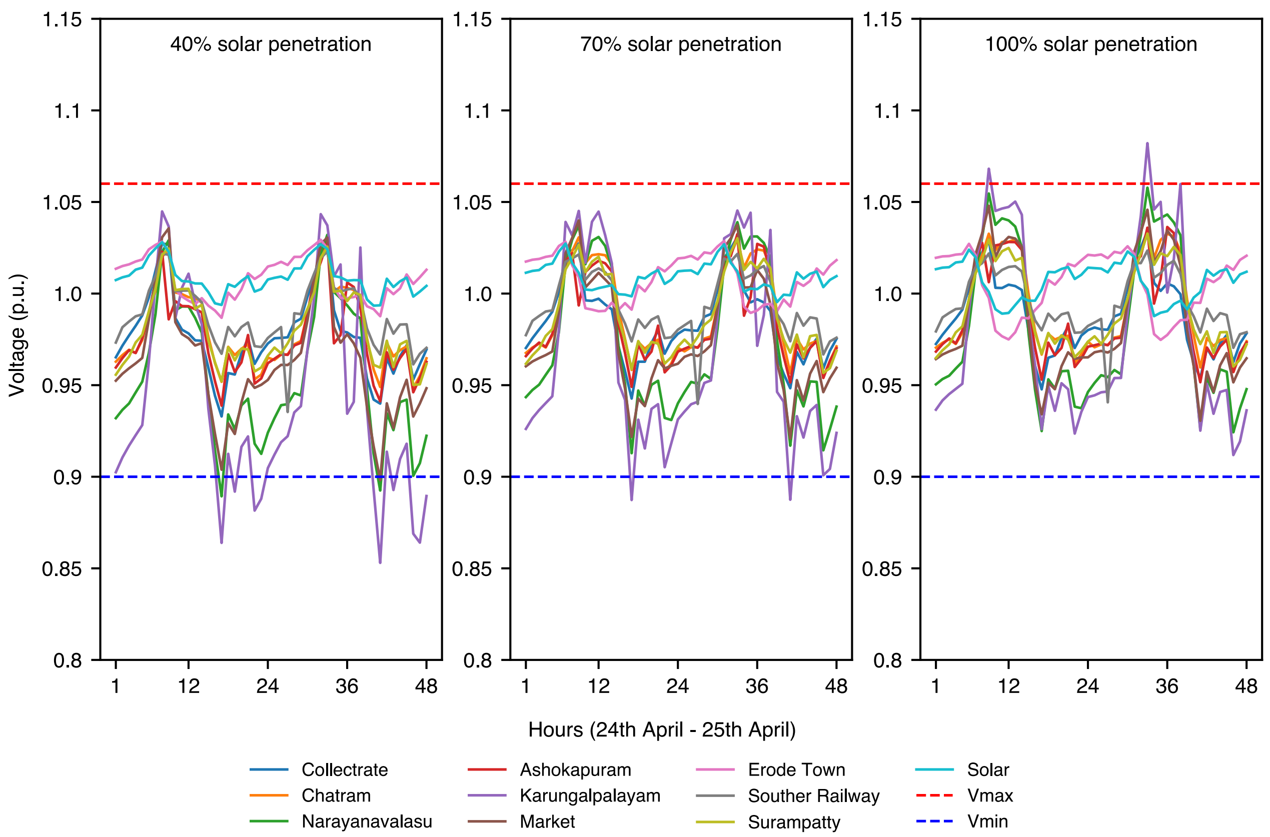
Figure 14 : Net active power for different solar penetration with ToD tariffs



Voltage

With the increases in solar energy penetration, there is an improvement in the voltage profile for all the feeders, as in the case of solar energy penetration without ToD tariffs. With and without ToD tariffs, Town and Solar Feeder maintain almost the same voltage profile for all simulated solar energy penetrations. For 100% solar penetration, upper limit violations can be seen during peak solar hours where there is high surplus solar beyond substation and the voltage violation is 5.97% of the time (Refer to Figure 15). On the other hand, for 70% of solar energy penetration, voltage violations are lower when compared to all other solar penetration simulated, occurring only 4.65% of the time.

Figure 15: Feeder voltage during peak demand hours from 24th – 25th April 2018 with ToD tariffs

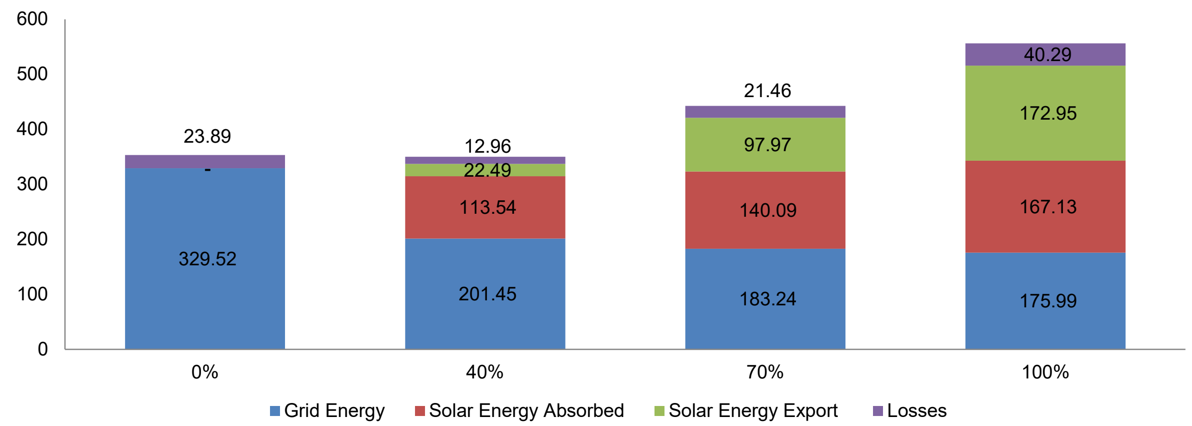


Distribution losses

As of result of the reduction in voltage drops over the feeders, the distribution losses also drop significantly (refer Table 11). On an average there is 0.3% reduction in losses compared to solar penetration scenarios without TOD tariffs. Savings related to reduction in distribution losses can be seen in Table 13.

With the introduction of ToD tariffs, the solar energy absorbed within the network increases and energy exported beyond the substation decreases when compared to the solar penetration levels without ToD tariffs (Refer to Figure 16 and Figure 12).

Figure 16: Energy Balance with ToD tariffs



Financial Analysis:

Even in the 0% solar energy penetration, where no solar energy is produced, the introduction of ToD tariffs generates savings to TANGEDCO of 20.16% compared to the BAU. Introducing ToD tariffs results in increased financial gains for all solar penetration levels. It is important to notice that even in the 100% solar penetration scenario savings of 69.98% over BAU can be observed. This is explained due to load shifting from peak hours to solar energy generation hours. All the solar energy penetration levels with ToD tariffs show better financial results when compared to the scenarios without ToD tariffs (Refer to Table 11).

Table 11: Solar Penetration Analyses – Utility Category with ToD Tariffs

	0%	40%	70%	100%
Capacity Installed (MWp)	-	85.88	150.28	214.69
Solar Energy Produced (MU)	-	136.03	238.06	340.08
Grid Energy metered @ SS (MU)	329.52	201.45	183.24	175.99
Voltage Violations (%)	78.97%	10.41%	4.65%	5.97%
Reactive Power Support (%)	100.00%	75.30%	93.30%	119.00%
Distribution Losses (%)	7.82%	4.24%	7.02%	13.18%
Total CoS (INR Cr)	259.53	214.21	248.56	294.97
Revenue (INR Cr)	192.08	195.84	216.94	242.10
Net Revenue (INR Cr)	**(67.45)**	**(18.37)**	**(31.61)**	**(52.87)**
Savings over BAU Net Revenue[10](%)	**20.16%**	**82.38%**	**77.75%**	**69.98%**

Introducing ToD tariffs results in a reduction of grid energy supply and distribution losses and there is an increase in the solar energy absorbed within the distribution network for all the solar energy penetration levels (Refer to Table 12 and Table 13). The highest percentage reduction of distribution losses can be observed for the 40% solar energy penetration level.

Table 12: Reduction in grid supply and solar energy absorbed with and without ToD tariffs

Grid units supplied	**0%**	**40%**	**70%**	**100%**
With actual load (MU)	340.12	216.03	198.67	190.97
Load with ToD tariffs (MU)	329.52	201.45	183.24	175.99
Reduction in grid supply (MU)	10.6	14.58	15.43	14.98
Solar energy absorbed within feeders' network				
With actual load (MU)	-	113.54	140.09	167.13
Load with ToD tariffs (MU)	-	117.14	143.85	169.93
Increase in solar energy absorbed (MU)	-	3.60	3.77	2.80

[10] *For calculating the savings compared to the BAU scenario, the amount of energy supplied in the BAU is modified to match the energy supplied in the other scenarios.*

Table 13: Reduction in distribution losses reduction with ToD tariffs implementation

	0%	40%	70%	100%
Actual Load (MU)	25.10	14.55	23.73	43.08
Load with ToD tariffs (MU)	23.89	12.96	21.46	40.29
Reduction in Losses with and without ToD Tariffs (MU)	1.21	1.59	2.27	2.79
Reduction in % of units supplied	**4.82%**	**10.93%**	**9.57%**	**6.48%**

Benefits in terms of CoS reduction due to ToD tariffs implementation can be seen in Table 14. Reduction in CoS on account of ToD tariffs are highest under the 70% solar energy penetration scenario with INR Cr 12.69 followed by the 100% solar energy penetration scenario with savings for INR Cr 12.57. Comparing the reduction in CoS for each solar penetration level with and without ToD tariffs, 40% solar energy penetration level with ToD tariffs results in the highest percentage wise CoS reduction (Refer to Table 14).

For the same solar energy penetration level, ToD tariffs implementation shows a reduction in financial losses to TANGEDCO in every scenario. This is on account of more solar energy being absorbed by the loads within the feeder distribution network (Refer to Table 15).

Table 14: Reduction in CoS due to ToD tariffs implementation

	0%	40%	70%	100%
Actual Load (INR Cr)	268.14	225.90	261.15	307.48
Load with ToD Tariffs (INR Cr)	259.53	214.12	248.47	294.90
Reduction in CoS (INR Cr)	8.61	11.78	12.69	12.57
Reduction in CoS (%)	**3.21%**	**5.21%**	**4.86%**	**4.09%**

Table 15: Savings due to ToD tariffs implementation

	0%	40%	70%	100%
Net Revenue Scenario without ToD Tariffs (INR Cr)	(84.48)	(36.41)	(51.51)	(75.80)
Net Revenue Scenario with ToD Tariffs (INR Cr)	(67.45)	(16.98)	(30.20)	(51.88)
Savings due to ToD Tariffs Implementation (INR Cr)	**17.03**	**19.43**	**21.31**	**23.92**
Savings due to ToD Tariffs Implementation (%)	**20.16%**	**53.36%**	**41.37%**	**31.56%**

4.4. Solar, ToD Tariffs & Storage | Maximizing Gains to TANGEDCO

To assess the impacts of energy storage, three simultaneous strategies are simulated: (i) solar PV penetration at 100% of the annual electricity consumption, (ii) demand side management in the form of ToD tariffs and (iii) energy storage in form of stationary MW scale lithium-ion batteries. For this analysis two out of the ten feeders were taken up: Karungalpalayam Feeder and Market Feeder. These two feeders were selected based on their comparatively high energy demand and their poor voltage profiles, with high instances of voltage violations (below the minimum allowable voltage). 95 MWh battery capacity is introduced for the Karungalpalayam Feeder and 102 MWh for the Market Feeder, which have an installed solar energy capacity of 28.75 MWp and 32.23 MWp respectively at 100% solar penetration. The battery capacity is designed to store 100% of surplus solar energy (solar energy which would otherwise have been exported beyond the substation) under the 100% solar energy penetration scenario. The battery storage system charges from 07:00h to 16:00h and discharges from 17:00h to 06:00h.

Technical Analysis:

Active Power

The peak demand for Karungalpalayam Feeder is on 3rd October 2018 at 12:00h. It is found that the units of electricity imported from beyond the substation significantly reduce with the introduction of storage. Most of the energy consumption is met either from solar or from storage (Refer to Figure 17). During battery discharging hours, there is an export of electricity beyond the substation from 17:00h to 01:00h. During battery charging hours, most of the surplus solar energy is stored and energy export beyond the substation is minimized (Refer to Table 17 and Table 18). Before the introduction of energy storage, the surplus solar energy under the 100% solar penetration scenario plus ToD tariffs is 18.98 MWh. After the introduction of energy storage the surplus solar export is reduced to 1.38 MWh. The peak demand of Market Feeder is recorded for 22nd October 2018, 12:00h. A similar pattern as with Karungalpalayam Feeder can be observed. There is a reduction in export of surplus solar energy from 24.93 MWh to 1.23 MWh. Most of energy stored is consumed during night time peak hours, thereby improving the feeders' efficiency.

Voltage

During storage charging hours (from 07:00h to 16:00h), voltage is low compared to feeder voltage without storage because of reduced surplus solar power in the distribution network. The voltage profile improves during discharging hours (Refer to Figure 17 and Figure 18). For Karungalpalayam Feeder, a 5.42% voltage violation is recorded before energy storage. This is reduced to 0.42% after the introduction of energy storage. For the Market Feeder, a 0.46% voltage violation was found with 100% solar energy penetration. After introducing energy storage, no voltage violation was observed at all (Refer to Table 18). The reduction in energy export helps to improve voltage and to reduce distribution losses for feeders.

Figure 17: Voltage and power of Karungalpalayam Feeder from 3rd to 4th October – ToD tariffs with Storage Scenario

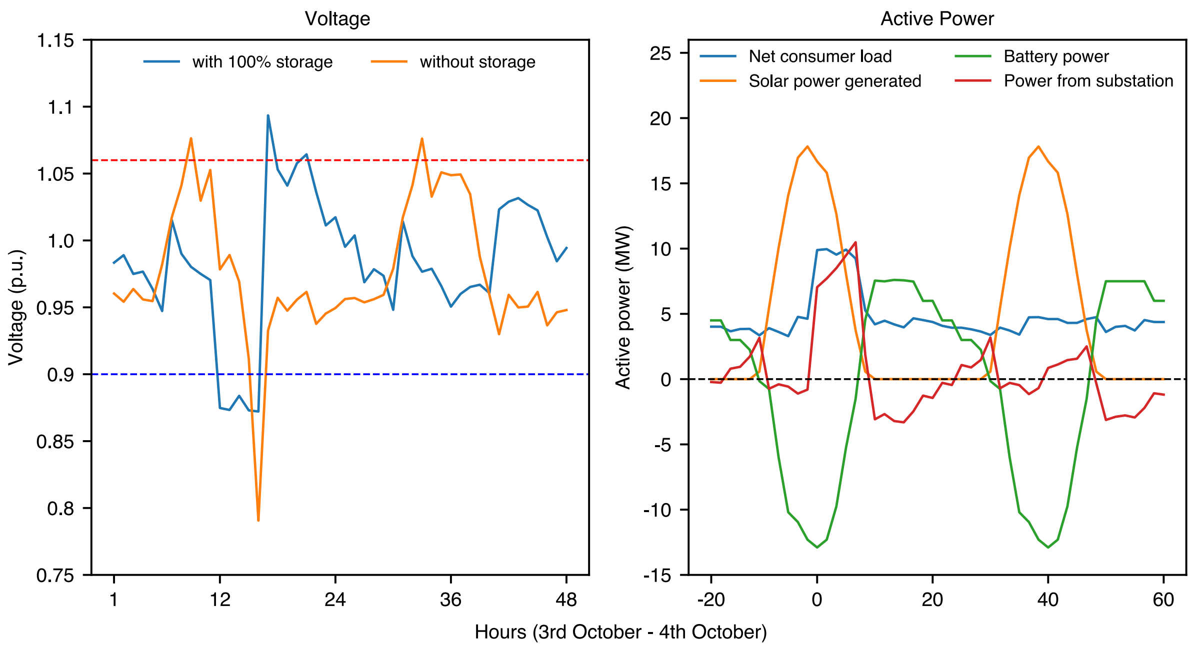
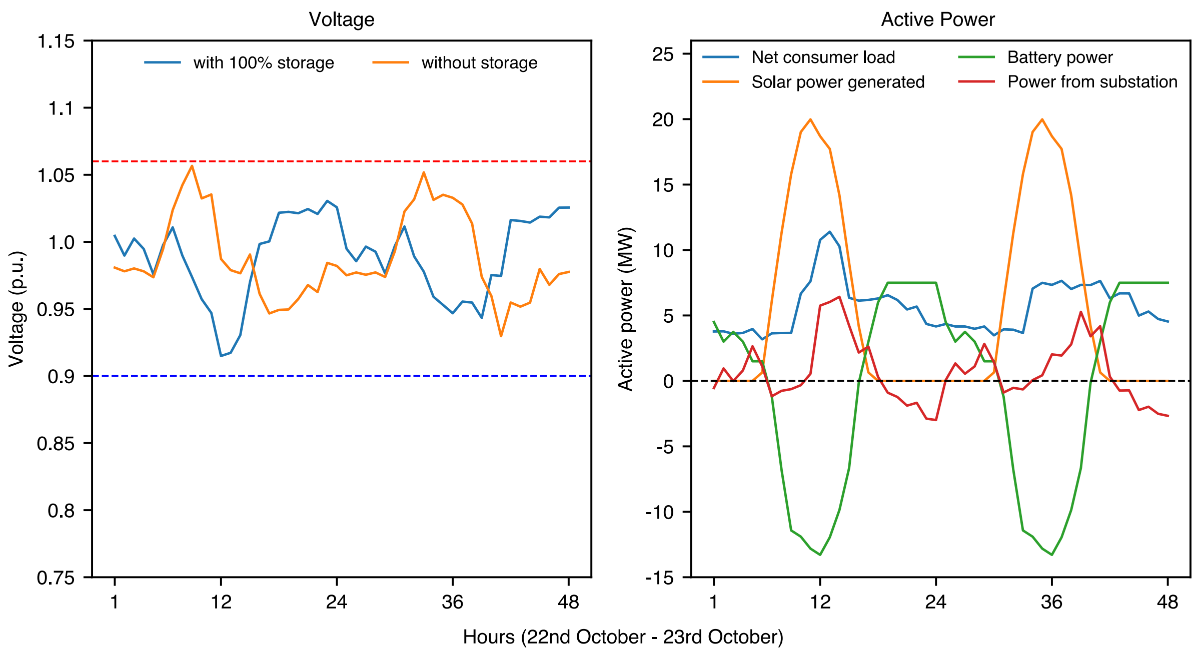


Figure 18: Voltage and power of Market Feeder from 22nd to 23rd October– ToD tariffs with Storage scenario



Distribution losses

There is a significant reduction in distribution losses due to lesser amount of energy flowing along the Karungalpalayam and the Market Feeder compared to the BAU scenario. With energy storage systems, losses for the Karungalpalayam Feeder reduce from 18.44% (BAU) to 5.78%. For the Market Feeder, losses reduce from 8.97% (BAU) to 2.31% (Refer to Table 17 and Table 18).

Feeder Capacity

For the 70% and 100% solar energy penetration levels the current hosting capacity (10 MW) is exceeded for both feeders without energy storage systems. With the introduction of energy storage along with the 100% solar penetration level no feeder capacity violation can be found. For the 22 kV Karungalpalayam Feeder the peak power flow from the solar plus energy storage system is 8.29 MW. For the 22 kV Market Feeder this is 7.98 MW.

Table 16: Peak power flow (in MW) from solar + solar plus storage energy system to Karungalpalayam and Market Feeder

Feeder	Peak Power (MW)			
	40%	70%	100%	100% solar + storage
Karungalpalayam Feeder	7.59	13.28	18.98	8.29
Market Feeder	8.51	14.89	21.27	7.98

Financial Analysis:

The three-tier implemented strategy of solar energy, ToD tariffs and energy storage shows positive technical and commercial results. Total CoS shows an accentuated reduction in each scenario, reducing TANGEDCO's losses further every time one of these three strategies is added. A 100% solar energy penetration, combined with ToD tariffs rates and energy storage achieves the most promising results (Refer to Table 17 and Table 18). Under 100% solar energy penetration without storage, there is a solar energy generation of which a part needs to be transported, resulting in: (i) an increase in distribution losses and (ii) an increase in total CoS on account of higher distribution losses. The ToD tariffs shift the demand to solar energy generation hours, therefore minimizing distribution losses and reducing total CoS. With the introduction of energy storage, distribution losses and CoS reduce further.

Table 17: Karungalpalayam Feeder analysis solar plus storage

Karungalpalayam Feeder	**0% (BAU)**	**100%**	**100% + ToD**	**100% + ToD + Storage**
Solar Energy Capacity Installed (MWp)	-	28.75	28.75	28.75
Solar Energy Produced (MU)	-	45.53	45.53	45.53
Storage Capacity (MWh)	-	-	-	105
Energy Stored/year (MU)	-	-	-	29.92
Grid Energy Metered @ Feeder Level	45.55	25.78	23.75	5.82
Voltage Violations	87.07%	8.26%	5.42%	0.42%
Reactive Power Support (%)	100.00%	94.20%	96.20%	81.40%
Distribution Losses (%)	18.44%	35.51%	34.20%	5.78%
Total CoS (INR Cr)	38.08	44.42	42.49	34.00
Revenue (INR Cr)	22.54	29.69	30.36	28.09
Net Revenue (INR Cr)	**(15.66)**	**(15.74)**	**(12.13)**	**(5.91)**
Savings over BAU Net Revenue[11](%)	**-**	**38.14%**	**45.74%**	**58.89%**

Table 18: Market Feeder analysis solar plus storage

Market Feeder	**0% (BAU)**	**100%**	**100% + ToD**	**100% + ToD + Storage**
Solar Energy Capacity Installed (MWp)	-	32.23	32.23	32.23
Solar Energy Produced (MU)	-	51.03	51.03	51.03
Storage Capacity (MWh)	-	-	-	105.00
Energy Stored/year (MU)	-	-	-	31.41
Grid Energy Metered @ Feeder Level (MU)	51.07	28.13	23.75	7.40
Voltage Violations	15.71%	0.19%	0.46%	aprox. 0%
Reactive Power Support (%)	100.00%	111.00%	112.00%	90.00%
Distribution Losses (%)	8.97%	14.08%	13.23%	2.31%
Total CoS (INR Cr)	36.40	45.77	39.79	35.72
Revenue (INR Cr)	24.11	34.62	25.25	32.25
Net Revenue (INR Cr)	(12.29)	(11.15)	(6.25)	(3.47)
Savings over BAU Net Revenue[11](%)	**-**	**49.20%**	**63.11%**	**76.69%**

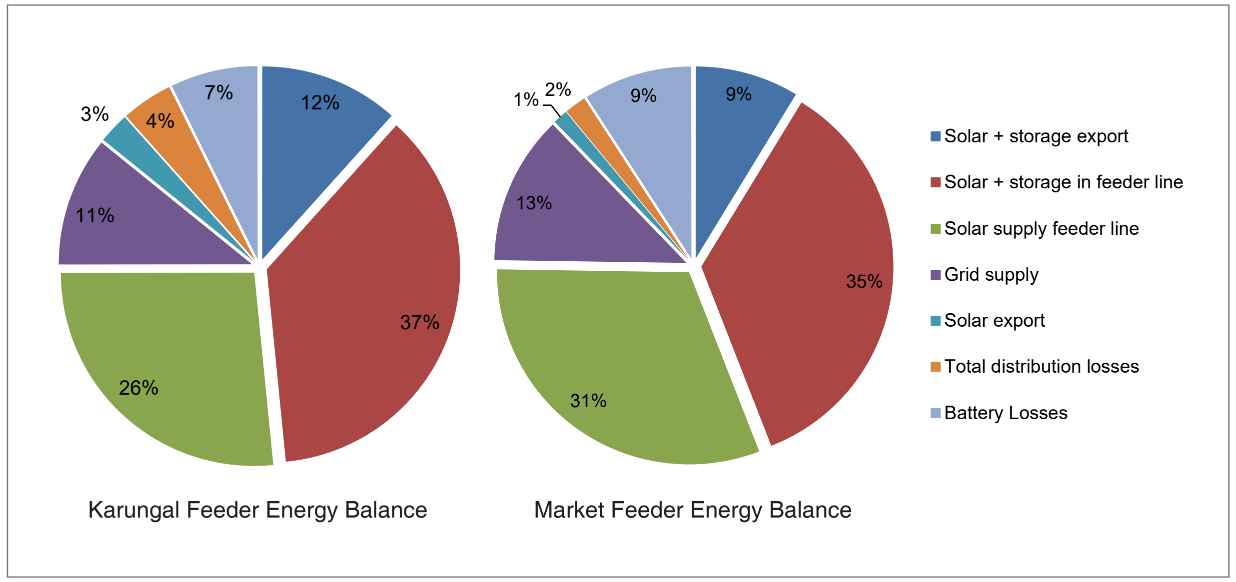
[11] *For calculating the savings compared to the BAU scenario, the amount of energy supplied in the BAU is modified to match the energy supplied in the other scenarios.*

According to the energy balance shown in Figure 19 and Table 19, the majority of energy supplying the load in each of the two selected feeders is supplied by the energy storage system (stored solar energy), followed by solar energy directly absorbed within the feeders. Grid supply from beyond the substation and solar energy export (beyond the substation) is reduced, when compared to the scenario without storage. Since grid energy is more expensive and export is less attractive when compared to solar energy used on the distribution network, savings are higher in this scenario, despite the higher total cost of solar energy plus storage. This can be explained by voltage drop reductions and reductions in line losses.

Table 19: Karungalpalayam and Market Energy Balance (in MU)

	Karungalpalayam	**Market**
Solar Plus Storage Export (MU)	6.26	5.15
Solar Plus Storage In Feeder Line (MU)	19.73	20.85
Solar Supply Feeder Line (MU)	14.26	18.39
Grid Supply (MU)	5.82	7.4
Solar Export (MU)	1.38	0.73
Total Distribution Losses (MU)	2.3	1.08
Battery Losses (MU)	3.93	5.4
Total Solar Power (MU)	45.53	51.03
Stored Solar Energy (MU)	25.99	26

Figure 19: Karungalpalayam and Market Feeder Energy Balance (as 100 % solar penetration plus storage)



A 25 years analysis was conducted, where solar energy plus energy storage prices were kept constant, while TANGEDCO's fixed costs and the average Power Purchase Cost (PPC) increase over time by an assumed inflation rate. The LCOE of solar plus storage is assumed at INR 6.97 per kWh. This value is based on the peak tariff discovered in a competitive bidding process for a combination or solar energy and storage by SECI in August 2019 (Solar Media Limited, 2020)[12]. TANGEDCO's PPC in FY 2018-19 stood at INR 5.83 per kWh. This is before distribution losses. For the Karungalpalayam Feeder, total CoS under 100% solar penetration with ToD tariffs plus storage is lower than the total revenue collection by TANGEDCO in the first 11 years. However, from year 12 onwards, the solar, ToD tariffs plus storage revenue exceeds the total CoS on account of a 25 years fixed solar energy tariff. For the Market Feeder, it becomes more attractive after the first 6 years, as revenue exceeds total CoS (Refer to Table 20). It is important to notice that under BAU, revenue never exceeds total CoS. In fact, there is a loss of INR Cr 266.10 for Karungalpalayam Feeder and a loss of INR Cr 277.87 for Market Feeder over 25 years. 94.87% savings over BAU for Karungalpalayam Feeder and 104.42% savings for Market Feeder can be achieved on a 25-year horizon. For more details on key assumptions refer to Appendix F – Financial Calculations.

Table 20: CoS per unit breakdown ToD tariffs plus Storage

	Karungalpalayam	Market
CoS Grid Energy per kWh	7.79	7.59
CoS within Distribution Network per kWh Solar	4.40	4.29
CoS Beyond Feeder Distribution Network per kWh Solar	4.52	4.29
CoS Solar Plus Storage per kWh	8.55	8.31

Table 21: NPV Results for 25 years

	Karungalpalayam	Market
BAU NPV (25 years)	(266.10)	(277.87)
NPV 100% Solar Plus Storage Revenue (25 years)	336.79	386.56
NPV CoS (25 years)	(350.44)	(371.51)
100% Solar Penetration Plus Storage NPV (25 years)	(13.65)	15.05
Net Revenue (25 year)	(0.04)	0.04
Savings over BAU Net Revenue	**94.87%**	**104.42%**
Revenue Exceeds Total CoS (Positive Net Revenue)	**from year 12 onwards**	**from year 7 onwards**

The techno-commercial results of deploying solar energy, ToD tariffs, and energy storage are very promising. Significant technical benefits such as voltage profile improvement and reduction in distribution losses can be found. A reduction in the overall CoS results in financial savings to TANGEDCO. One-year savings for the Market Feeder, when 100% solar penetration, energy storage and ToD tariffs are introduced, exceeds the savings obtained under the 40% solar penetration level plus ToD tariffs scenario.

[12] *Selection of Project Developers for setting up of 1200 MW ISTS-Connected RE Projects with assured Peak Power Supply in India (ISTS-VII)/ RfS No. SECI/C&P/HPD/ISTS-VII/RfS/1200MW/082019. Dated: 01.08.2019.*

5. SIMULATING IMPACTS ON CONSUMER CATEGORY (BEHIND-THE-METER) | CONSUMER CATEGORY SOLAR AS COST REDUCTION STRATEGY

For the techno-commercial impact analysis of Consumer Category solar the electricity consumer categories were grouped into four: Residential, Commercial, Industrial and Others. Residential, Commercial and Industrial consumer account for 98.98% of the total electricity consumption at Erode Substation. All the consumers under a single DT (DT26) of Collectrate Feeder were used for the analysis. Monthly average load curves with hourly time intervals were created for the Residential, Commercial, Industrial and Other consumer categories. This was done using TERI's recorded load shapes for Tamil Nadu (TERI, 2012), the bi-monthly energy consumption data for 2018 and the connected load recorded for these consumer categories. These load curves were utilized to determine the solar energy self-consumption potential, surplus solar energy exported and grid energy consumed by the Residential, Commercial and Industrial consumer categories. Solar energy for the category 'Other' has not been considered for this analysis (Refer to Appendix B – Load curves).

Results of all consumer categories have been aggregated on the DT level in order to assess the commercial and technical impact of solar energy penetration, ToD tariffs plus battery storage on the low voltage distribution network.

For the solar energy penetration levels rooftop solar system capacities were standardized for the 3 Consumer Categories at 3 kW for Residential, 10 kW for Commercial and 25 kW for Industrial consumers[13]. With higher solar energy penetration, the number of consumers solarised increases. Table 22 summarized the number of consumers solarised, the total solar energy capacity and the total solar energy generation by consumer categories.

In 2018, Residential consumers account for 38.81% of the total electricity consumption on DT26 of Collectrate. Under the 100% solar energy penetration scenario, 52 residential homes were assumed to be solarised, each with a 3 kW solar system. The total installed solar energy capacity for Residential consumers is 155.94 kWp, generating 241.93 MWh of solar energy annually. 16 Commercial consumers with a solar capacity of 10 kW and 4 Industrial consumers with a solar capacity of 25 kW were assumed solarised under the 100% solar energy penetration scenario. The total solar energy capacity and annual solar energy generation is 158.35 kWp and 245.72 MWh for Commercial consumers and 84.23 kWp and 129.37 MWh for Industrial consumers. The aggregated solar energy generated by all systems is equal to the yearly energy consumption of all consumers connected to DT26.

[13] *For Residential Category, 40% capital subsidy is provided for solar systems up to 3 kW under phase 2 of MNRE's Rooftop Solar Program. Therefore 3 kW solar has been used as standard size for Residential consumers. For Commercial and Industrial consumers, it was assumed that a higher electricity consumption requires higher solar capacities. Industrial consumers may have a higher rooftop availability therefore a 25 kW of solar was assumed.*

Table 22: Summary of Consumer Category solar generation

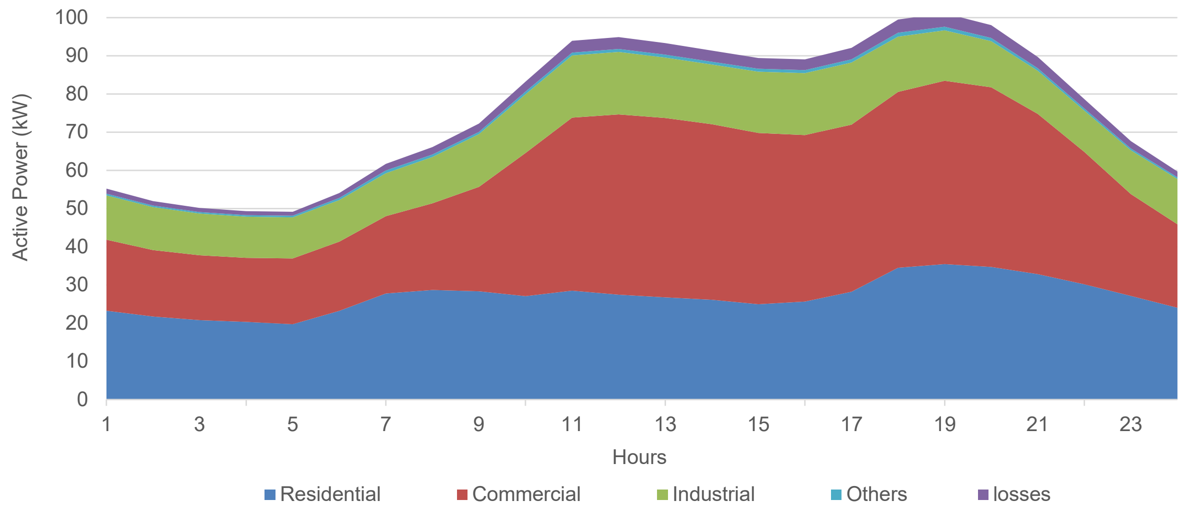
				40%			70%			100%		
Consumer Category	**Total Electricity Consumption (MWh)**	**Solar Energy Capacity (per Consumer) kW**	**Total Number of Consumers**	**Number of Consumers Solarised**	**Total Installed Solar Capacity (kWp)**	**Solar Energy Gross Generation (MWh)**	**Number of Consumers Solarised**	**Total Installed Solar Capacity (kWp)**	**Solar Energy Gross Generation (MWh)**	**Number of Consumers Solarised**	**Total Installed Solar Sapacity (kWp)**	**Solar Energy Gross Generation (MWh)**
Residential	241.93	3	170	21	62	96.76	37	109	169.35	52	155.94	241.93
Commercial	245.72	10	72	7	63	98.29	11	111	172.09	16	158.35	245.72
Industrial	129.38	25	9	2	34	51.76	3	59	90.51	4	84.23	129.37
Other	6.36	0	0	0	0	0	0	0	0	0	0	0

5.1. Business-as-Usual (BAU) | High Net Revenue Losses to TANGEDCO

Technical Analysis:

The simulation shows that the monthly average peak demand occurs at 19:00h in November 2018 (Refer to Figure 20). The calculated distribution losses within the DT network are 3.02%. Voltages in the DT network are within the acceptable limit for all hours (Refer to Figure 22 and Table 24).

Figure 20: Average daily active power for BAU Scenario in November 2018



Financial Analysis:

For calculation of the CoS, it was assumed that the technical losses beyond the DT are 4.89%. Similar to Utility Category solar, a gap between CoS and TANGEDCO's net revenue of INR 3.44 per kWh can be found. The total net revenue gap to TANGEDCO for the DT26 distribution network in 2018 stood at INR Cr (0.14) or -22.89% of total revenue (Refer to Table 23).

Table 23: Financial Analysis BAU scenario – Consumer Category

	Value
Grid Energy Metered @ DT network (MU)	0.64
Losses (MU)	1.90
Consumer Loads (MU)	0.62
CoS per unit Grid Energy (INR per kWh)	7.91
Total Cost of Energy Supply within Distribution Network (INR Cr)	0.51
Total Revenue (INR Cr)	0.37
Net Revenue (INR Cr)	**(0.14)**
Net Revenue (in %)	**-22.89%**

5.2. Solar Penetration Levels | Feeding the Grid from the Tail-end

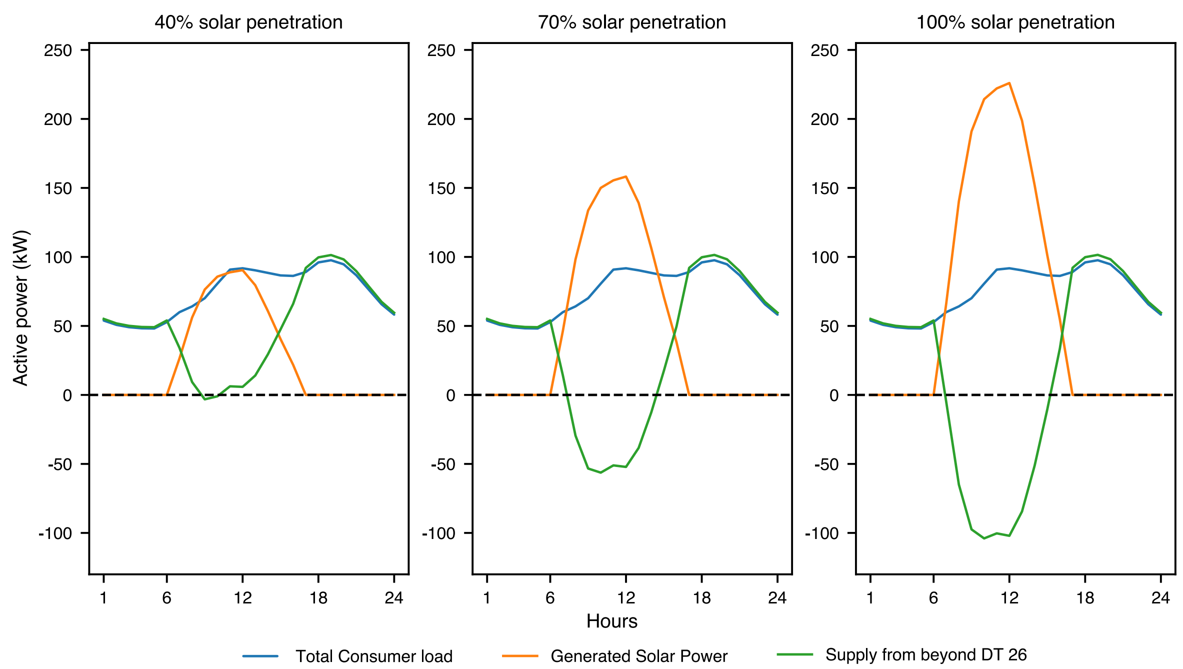
The solar capacity used for Residential, Commercial and Industrial consumer categories are 3 kWp, 10 kWp and 25 kWp respectively. As the solar capacity for each consumer Category has been fixed, the number of consumers with rooftop solar for each of the solar energy penetration scenario varies. For details refer Appendix C – Solar and storage systems.

Technical Analysis:

Active power

It is found that 40% solar energy penetration is sufficient to serve the consumer loads during peak solar generation hours. The average surplus solar energy flowing beyond DT26 per day is 0.03 MWh for the 40% scenario, 0.37 MWh for the 70% scenario and 0.73 MWh for the 100% scenario. For the 40% solar penetration scenario, the surplus solar energy flowing beyond the DT occurs from 9:00h to 14:00h, for the 70% scenario it occurs from 8:00h to 15:00h and for the 100% scenario it occurs from 7:00h to 16:00h (Refer to Figure 21).

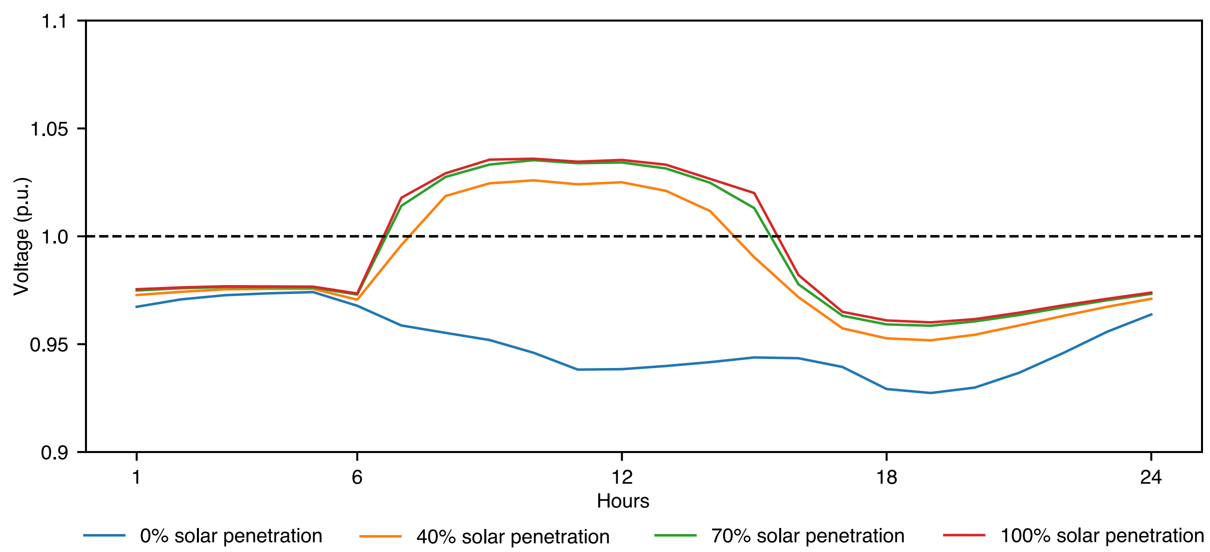
Figure 21: Active power for different penetration in November – Consumer Category



Voltage

Voltage is within the acceptable limits for the BAU scenario, however a consistently low voltage profile can be observed. With increasing solar energy penetration, the voltage profile is improving. Voltage improvements are also observed during non-solar hours, on account of the reactive power support from the smart solar inverter (Refer to Figure 22).

Figure 22: Voltage profile for Consumer Category



The introduction of Consumer Category solar results in a voltage increase at the consumers' service connection points. During solar energy generation hours, the voltage profile shifted from the lower bound (0.9-0.98 p.u.) to the upper bound (0.98-1.06 p.u.) (Refer to Table 24). For the 100% solar penetration level, voltages at the majority of the service connections are in the range of (1.02-1.06 p.u.). For the 70% and 100% solar penetration levels, a few service connection points have voltages above the upper limit of 1.06 p.u. For any of the solar penetration level, voltage is never found to be in the lowest range (0.9-0.94 p.u.).

Table 24: Percentage of service connection points in different voltage ranges and solar energy penetrations

	01:00h - 9:00h				09:00h - 17:00h				17:00h-24:00h			
Voltage Range (p.u.)	0% (BAU)	40%	70%	100%	0% (BAU)	40%	70%	100%	0% (BAU)	40%	70%	100%
0.9-0.94	0.26%	0.00%	0.00%	0.00%	5.15%	0.00%	0.00%	0.00%	29.59%	0.00%	0.00%	0.00%
0.94-0.98	65.21%	49.96%	47.88%	43.30%	66.75%	0.89%	1.35%	0.71%	43.96%	74.00%	72.44%	70.14%
0.98-1.02	34.54%	46.14%	39.92%	38.19%	28.11%	31.30%	16.16%	10.71%	26.46%	26.00%	27.56%	29.86%
1.02-1.06	0.00%	3.90%	12.21%	18.46%	0.00%	67.82%	82.20%	88.04%	0.00%	0.00%	0.00%	0.00%
> 1.06	0.00%	0.00%	0.00%	0.05%	0.00%	0.00%	0.29%	0.54%	0.00%	0.00%	0.00%	0.00%

Distribution Losses

With an increase in solar penetration, from 0% to 100%, an increase in distribution losses from 3.02% to 8.59% is found for the distribution network of DT26. This increase in distribution losses is on account of higher units of solar energy flowing back to the substation from the solar generators compared to the energy flowing under BAU scenario (Refer to Table 25).

Energy Balance

Compared to BAU there is a reduction of grid energy drawn of 0.23 MU under the 40% scenario, 0.27 MU under the 70% scenario and 0.28 MU under the 100% scenario. Solar self-consumption proportionally increases with increase in solar penetration. Solar energy flow beyond the DT is low under the 40% scenario with 0.01 MU but increases for the 70% and 100% penetration scenario (Refer to Figure 23).

Figure 23: DT26 Energy Balance – Consumer Category under different solar penetration

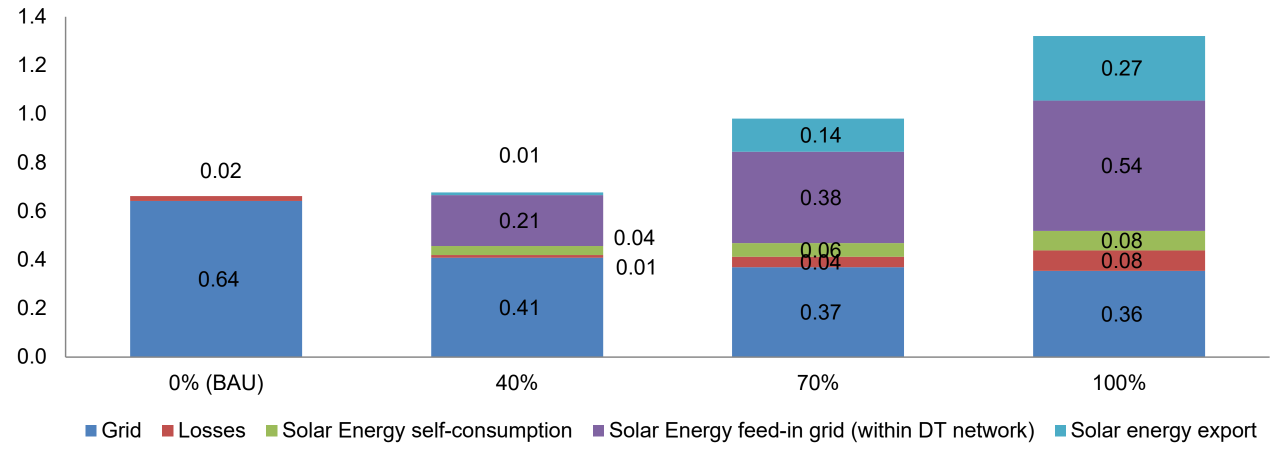


Table 25: Solar Penetration Analysis – Consumer Category

	0%	40%	70%	100%
# of Consumers Connected	-	28.48	49.83	71.18
Capacity Installed (MWp)	-	159.42	278.98	398.52
Solar Energy Produced (MU)	-	0.25	0.43	0.62
Grid Energy Metered @ DT (MU)	0.64	0.41	0.37	0.36
Distribution Losses After DT[14](%)	3.02%	3.22%	5.37%	8.59%
Total CoS (INR Cr)	0.51	0.40	0.48	0.59
Revenue (INR Cr)	0.37	0.36	0.49	0.63
Net Revenue (INR Cr)	**(0.14)**	**(0.04)**	**0.01**	**0.05**
Savings over BAU Net Revenue[15](%)	**-**	**70.45%**	**104.00%**	**109.64%**

[14] *Distribution losses only after the distribution transformer (DT26). Values beyond the transformer were calculated as 4.89%.*

[15] *For calculating the savings compared to the BAU scenario, the amount of energy supplied in the BAU is modified to match the energy supplied in the other scenarios.*

Financial Analysis:

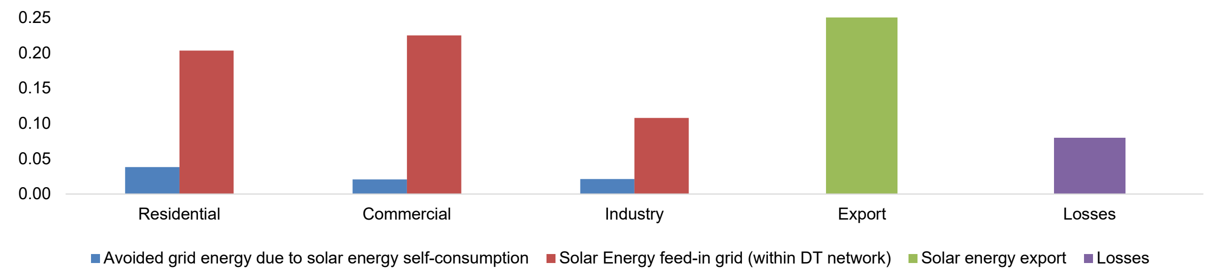
Unlike the results presented for the Utility Category solar in chapter 3, financial savings to TANGEDCO for the 100% solar energy penetration scenario are higher for the Consumer Category solar. TANGEDCO's financial losses of INR Cr 0.14 under BAU turned into a net gain of INR Cr 0.05, resulting in cost savings of 109.64% compared to BAU. TANGEDCO's savings compared to the BAU scenario for the 70% solar energy penetration are at 104.00% and 70.45% for the 40% solar energy penetration.

Assuming that the solar energy feed-in tariff is raised to INR 4.50 per kWh, which is a feed-in tariff closer to the LCOE of small scale solar energy systems, for the 40% solar penetration level a saving to TANGEDCO of 38.87% when compared to the BAU scenario can be found. For the 70% solar energy penetration level, savings over the BAU scenario would be at 62.86%. For the 100% solar energy penetration level, 68.21% savings can be achieved when compared to the BAU scenario.

Under the Consumer Category solar, the 70% and 100% solar penetration levels are financially attractive to TANGEDCO. This can be attributed to (i) a solar net feed-in tariff (INR 2.28 per kWh) for Consumer Category solar that is lower than the gross feed-in tariff (INR 3.04 per kWh) for the Utility Category of solar; and (ii) a large percentage of surplus solar energy that is absorbed by loads within the feeder, and therefore, no transmission losses are added (Refer to Table 25).

The solar energy self-consumption by the residential consumers with rooftop solar is estimated at 0.04 MU (41.6% per consumer total energy consumption), solar energy grid feed-in is at 0.20 MU. Solar energy self-consumption by the commercial and industrial consumers with Consumer Category solar is estimated at 0.02 MU (50.3% per consumer total energy consumption) and 0.02 MU (50.8% per consumer total energy consumption) respectively. All residential consumers with Consumer Category solar connected to DT26 contribute to a higher avoided grid import on account of self-consumption of solar energy as compared to the solarised commercial and industrial consumers (Refer to Figure 24).

Figure 24: Solar energy balance @ 100% solar penetration within DT26 network



The CoS per kWh, for both grid and solar energy, increases with higher solar energy penetration. This is explained by higher solar energy export and therefore an increase in distribution losses (Refer to Table 26).

Table 26: Cost per unit – Consumer Category

	0%	40%	70%	100%
CoS Grid Energy per kWh	7.91	7.93	8.05	8.24
CoS within Transformer Network per kWh Solar	3.53	3.53	3.58	3.66
CoS Beyond Transformer per kWh Solar	3.64	3.64	3.69	3.77

On the other hand, total CoS of grid energy decreases from INR Cr 0.51 to INR Cr 0.32 under the 40% solar energy penetration level. Further reduction of the total CoS of grid energy is found for the 70% and the 100% solar energy penetration levels. Reduction in the total CoS is at maximum for the 40% solar energy penetration level. There is an increase in total CoS from 70% to 100% solar penetration (Refer to Table 27).

Table 27: Total CoS Breakdown – Consumer Category

	0%	40%	70%	100%
Grid Energy (INR Cr)	0.51	0.32	0.30	0.29
Solar Energy within Transformer Distribution Network (INR Cr)	-	0.07	0.13	0.20
Solar Feed-in beyond DT Network (INR Cr)	-	0.00	0.05	0.10
Total CoS (INR Cr)	0.51	0.40	0.48	0.59

Total financial savings to TANGEDCO are INR Cr 0.09, INR Cr 0.17 and INR Cr 0.25 for 40%, 70% and 100% solar penetrations respectively. Reduction in CoS is shown in Table 28.

Reduction in CoS to TANGEDCO are calculated by comparing the CoS for each scenario to the BAU scenario. The increase in units of electricity supplied has been taken into consideration for the cost saving estimation. The units of electricity delivered increase with higher solar energy penetration levels. This is on account of surplus solar energy flowing beyond DT26 Collectrate Feeder. Reduction in CoS is the highest under 100% solar penetration with INR Cr 0.25 (Refer to Table 28).

Table 28: Reduction in total CoS – Consumer Category

	40%	70%	100%
Reduction in CoS within Transformer Distribution Network	0.09	0.17	0.25
Reduction in Cost due to feed-in Solar Energy Exported Beyond Distribution Transformer	0.03	0.05	0.07
Avoided Costs due to Self-consumption	0.12	0.21	0.31
Reduction in Total CoS Reduction	0.09	0.17	0.25

Differently than for the Utility Category, where an increase in solar penetration level beyond 40% results in a reduction of savings to TANGEDCO, for the Consumer Category solar, with increase in solar penetration, financial savings to TANGEDCO increases as well.

Under high solar energy penetration levels self-consumption of solar energy, in particular for the residential consumers, results in a saving to TANGEDCO as the AvBR for residential consumers is below the CoS. Surplus solar energy injected by the various consumers into the DT network comes at a cost of INR 2.28 per kWh to TANGEDCO, thereby also reducing TANGEDCO's total CoS. This surplus solar energy is resold at the ABR. As most of the surplus solar energy is consumed within DT26, the low cost of solar and the avoidance of distribution and transmission costs results in financial gains to TANGEDCO.

5.3. Solar Penetration & ToD Tariffs | Increasing Self-consumption

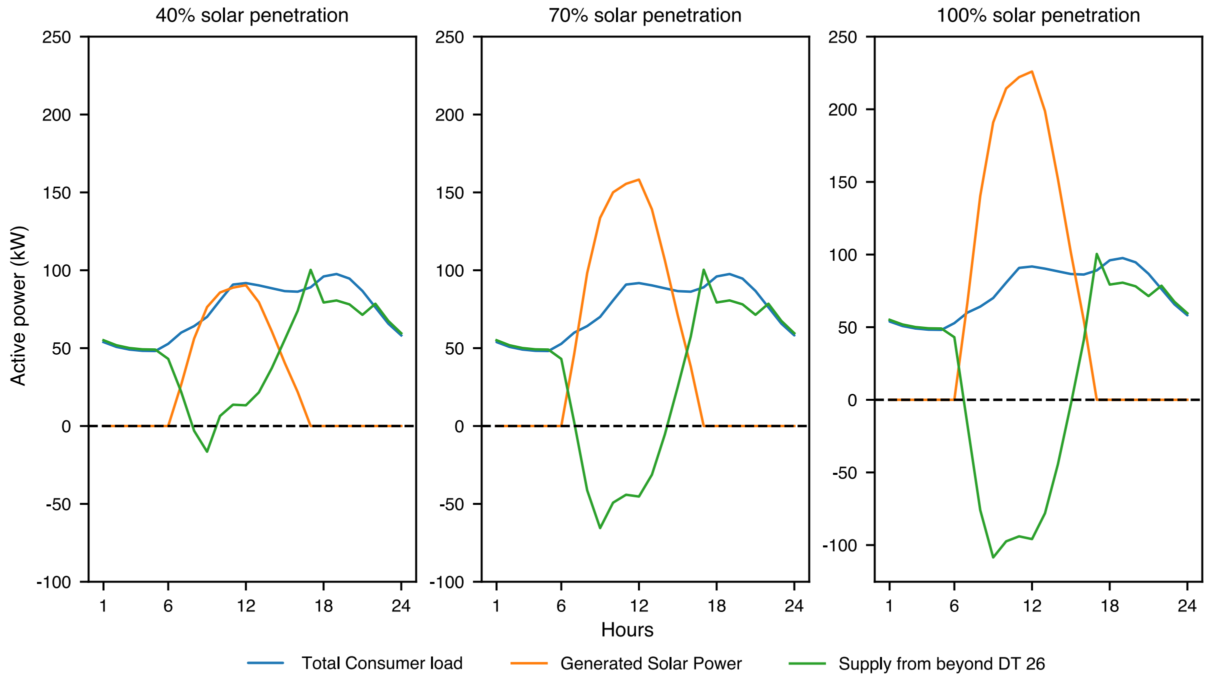
This chapter analyses the impacts of introducing ToD tariffs for the Consumer Category solar. Solar energy self-consumption and solar energy absorbed within the DT network is expected to be optimized by the introduction of ToD tariffs. The same assumptions taken for the Utility Category solar analysis were used for the analysis for Consumer Category solar.

Technical Analysis:

Active power

The average peak demand is at 19:00h in November 2018. 40% solar energy penetration is enough to serve the loads during peak solar generation hours. Under the 40% solar penetration around 0.03 MWh of average daily surplus solar energy is flowing beyond DT26. 0.36 MWh and 0.72MWh solar energy flows beyond the DT26 for the 70% and the 100% solar penetrations respectively (Refer to Figure 25). For the 40% solar penetration the surplus solar energy flowing beyond the DT occurs from 8:00h to 13:00h, for the 70% penetration it occurs from 8:00h to 14:00h and for the 100% penetration it occurs from 8:00h to 15:00h.

Figure 25: Active power for different solar penetration – Consumer Category with ToD tariffs



Voltage

Compared to the solar energy penetration without ToD tariffs, the introduction of ToD tariffs results in additional voltage improvements during peak hours. Without solar energy systems, there is an improvement in the voltage profile during 17:00h to 24:00h whereas more numbers of service connection points are in the lowest voltage range (0.9 – 0.94 p.u.) during 09:00h to 17:00h. With the deployment of solar energy systems, voltage profiles of the service connection points shifts from the lower bound (0.9-0.98 p.u.) to the upper bound (0.98-1.06 p.u.). For the 100% solar energy penetration level, voltage at the majority of the service connection points are in a range of 1.02-1.06 p.u. Small upper limit voltage violations can be seen under the 70% and the 100% solar energy penetration levels for the period 01:00h to 17:00h (Refer to Table 29 and Figure 26).

Figure 26: Voltage profile for different penetration – Consumer Category with ToD tariffs

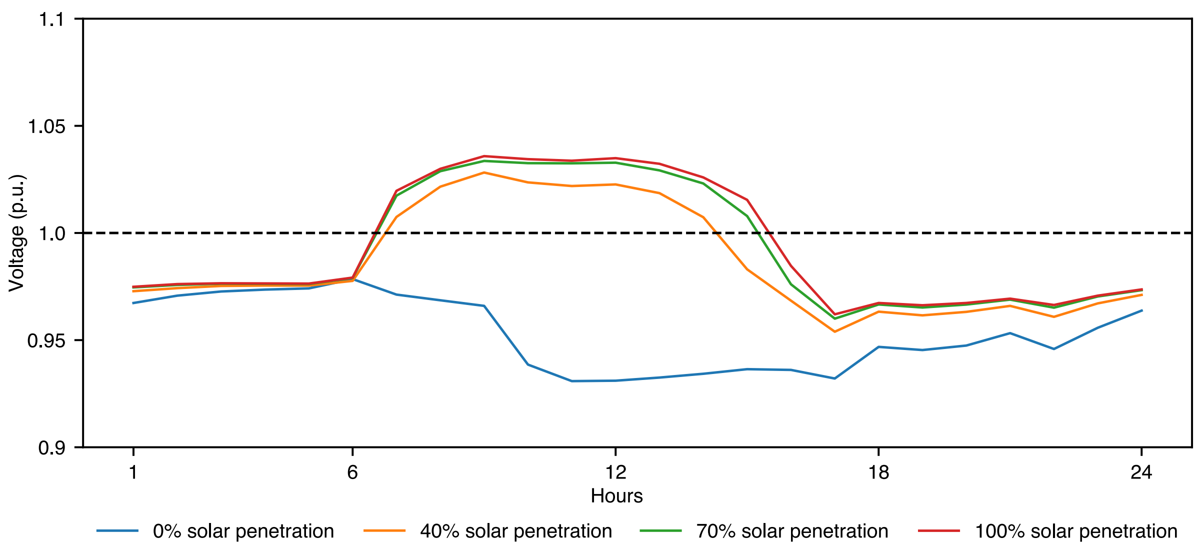


Table 29: Percentage of service connection points in different voltage ranges with ToD tariffs and solar energy penetrations

	01:00h - 09:00h				09:00h - 17:00h				17:00h-24:00h			
Voltage Range (p.u.)	0%	40%	70%	100%	0%	40%	70%	100%	0%	40%	70%	100%
0.9-0.94	0.26%	0.00%	0.00%	0.00%	28.07%	0.00%	0.00%	0.00%	10.83%	0.00%	0.00%	0.00%
0.94-0.98	63.58%	45.24%	42.09%	40.65%	47.42%	6.56%	1.72%	0.71%	62.98%	73.29%	72.73%	71.11%
0.98-1.02	36.16%	45.09%	43.56%	38.94%	24.51%	34.20%	18.51%	11.48%	26.19%	26.71%	27.27%	28.89%
1.02-1.06	0.00%	9.67%	14.33%	20.36%	0.00%	59.24%	79.50%	87.31%	0.00%	0.00%	0.00%	0.00%
> 1.06	0.00%	0.00%	0.02%	0.05%	0.00%	0.00%	0.27%	0.50%	0.00%	0.00%	0.00%	0.00%

Distribution Losses

Compared to the scenarios without ToD tariffs, introducing ToD tariffs shows reduction in distribution losses for all scenarios. Comparing the BAU scenario with the BAU scenario plus ToD tariffs an improvement in distribution losses from 3.02% to 2.97% can be found. For the solar penetration levels plus ToD tariffs the highest reduction in distribution losses of 0.17% can be observed for the 40% solar energy penetration scenario. The reduction in distribution losses for 70% and 100% solar penetration levels are 0.10% and 0.06% respectively (Refer to Table 30 and Figure 27).

Energy Balance

Compared to the BAU plus ToD tariffs scenario there is a reduction of grid energy drawn of 0.23 MU under the 40% solar penetration, 0.28 MU under the 70% solar penetration and 0.29 MU under the 100% solar penetration. There is a positive relation between solar energy self-consumption and solar energy penetration. Solar energy flow beyond the DT is low under the 40% scenario with 0.01 MU but increases for the 70% and 100% solar penetrations (Refer to Figure 27). Introducing ToD tariffs shows minor impacts on the solar self-consumption, even though loads are shifted to non-peak solar hours and moderate reduction in distribution losses.

Figure 27: DT26 Energy Balance with ToD tariffs

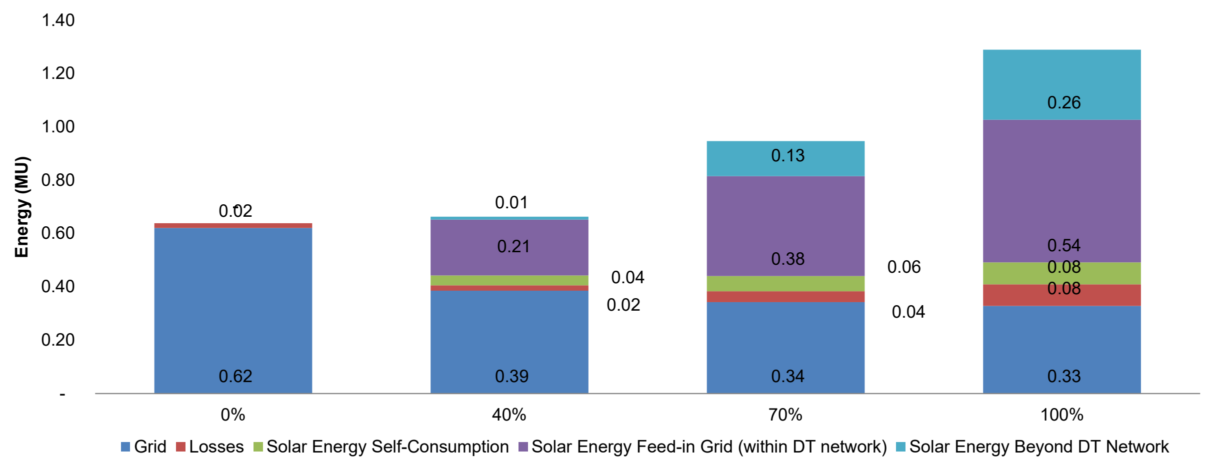


Table 30: Solar penetration plus ToD tariffs – Consumer Category

	0%	40%	70%	100%
# of Consumers Connected	-	28.48	49.83	71.18
Capacity Installed (kWp)	-	159.42	278.98	398.52
Solar Energy Produced (MU)	-	0.25	0.43	0.62
Grid Energy Metered @ DT (MU)	0.62	0.39	0.34	0.33
Distribution Losses[16](%)	2.97%	3.05%	5.27%	8.53%
Total CoS (INR Cr)	0.49	0.38	0.46	0.57
Revenue (INR Cr)	0.35	0.35	0.48	0.62
Net Revenue (INR Cr)	(0.14)	(0.04)	0.02	0.05
Savings over BAU Net Revenue[17](%)	**3.71%**	**74.54%**	**106.19%**	**111.17%**

Financial Analysis:

With the introduction of ToD tariffs, TANGEDCO's net revenue increases with every increase in solar energy penetration level. The highest savings over BAU net revenue can be observed for the 100% solar energy penetration level (Refer to Table 30).

There is a reduction in CoS with the introduction of ToD tariffs for all solar energy penetration levels. The reduction of CoS on account of introducing ToD tariffs as compared to the scenarios without ToD tariffs is in the range of INR Cr 0.02 (Refer to Table 31).

[16] Distribution losses only after the distribution transformer (DT26). Values beyond the transformer were calculated as 6.98%.
[17] For calculating the savings compared to the BAU scenario, the amount of energy supplied in the BAU is modified to match the energy supplied in the other scenarios.

Table 31: Reduction in CoS due to ToD tariffs implementation – Consumer Category

	0%	40%	70%	100%
CoS (without ToD tariffs) (INR Cr)	0.51	0.40	0.48	0.59
CoS (with ToD tariffs) (INR Cr)	0.49	0.38	0.46	0.57
Savings (INR Cr)	0.02	0.02	0.02	0.02
Savings (in % of CoS)	**3.92%**	**5.00%**	**4.17%**	**3.39%**

Introducing ToD tariffs increase savings to TANGEDCO. With the implementation of ToD tariffs, the savings are 0.005 INR Cr for the BAU case. The maximum savings of 0.007 INR Cr can be expected for the 100% solar penetration with ToD tariffs (Refer to Table 32).

Table 32: Savings due to ToD tariffs implementation – Consumer Category

	0%	40%	70%	100%
Net Revenue (with ToD tariffs) (INR Cr)	(0.142)	(0.043)	0.012	0.046
Net Revenue (without ToD tariffs) (INR Cr)	(0.137)	(0.037)	0.018	0.053
Savings due to ToD Tariffs Implementation (INR Cr)	0.005	0.006	0.006	0.007
Savings due to ToD Tariffs Implementation (in % of Net Revenue)	**3.52%**	**13.95%**	**50.00%**	**15.22%**

5.4. 100% Solar Penetration, ToD Tariffs & Storage | Maximum Benefits

For this analysis, battery storage systems are introduced for the scenario with 100% solar energy penetration plus ToD tariffs. The battery capacity of each consumer category is designed to store 100% of surplus solar (solar energy that would otherwise have been exported beyond the service connection point). The battery capacities used are 10 kWh, 50 kWh and 80 kWh for residential, commercial and industrial categories respectively. The battery storage systems is in charge mode from 07:00h to 17:00h and discharge mode from 17:00h to 07:00h.

Technical Analysis:

Active power

It is found that the units of electricity flowing beyond the DT to the distribution network significantly reduce with the introduction of energy storage. Using energy storage systems, most of the solar surplus energy can be stored and dispatched during non-solar hours especially between 17:00h to 21:00h (Refer to Figure 28).

Figure 28: Active power for Consumer Category with storage and comparison of active downstream the DT

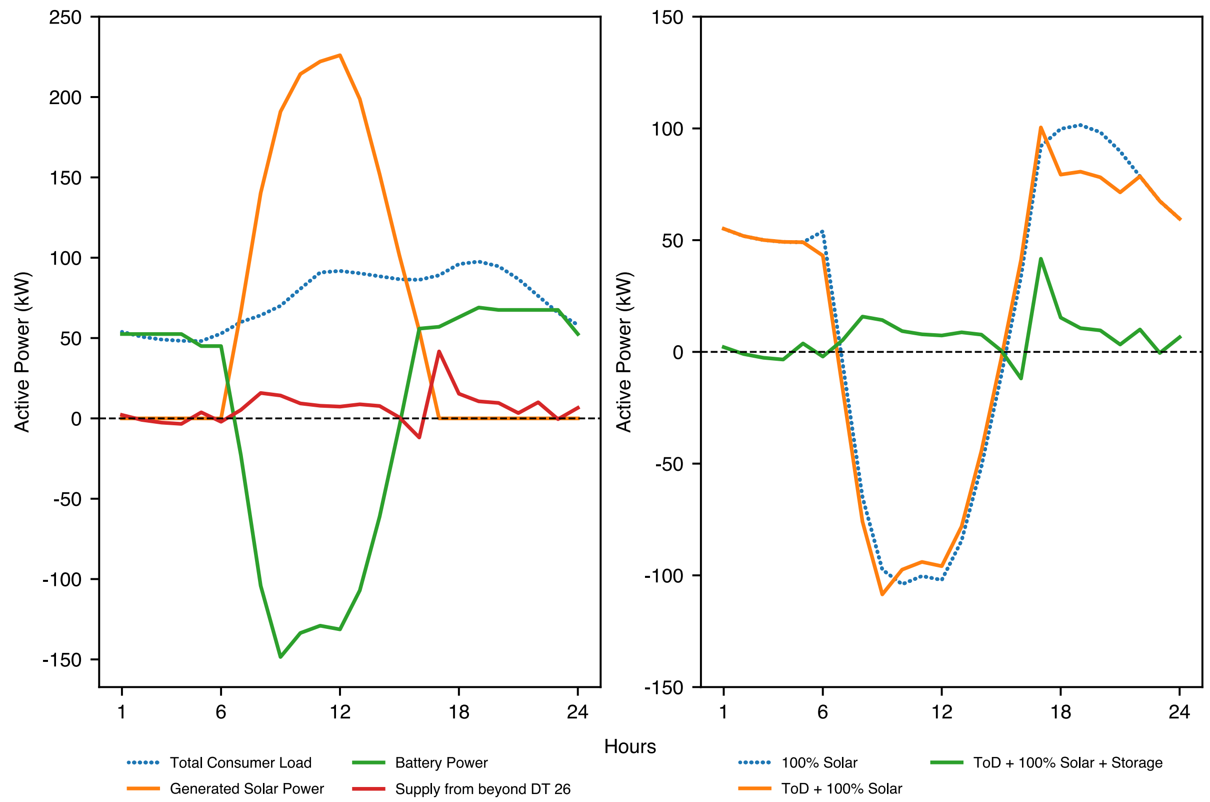
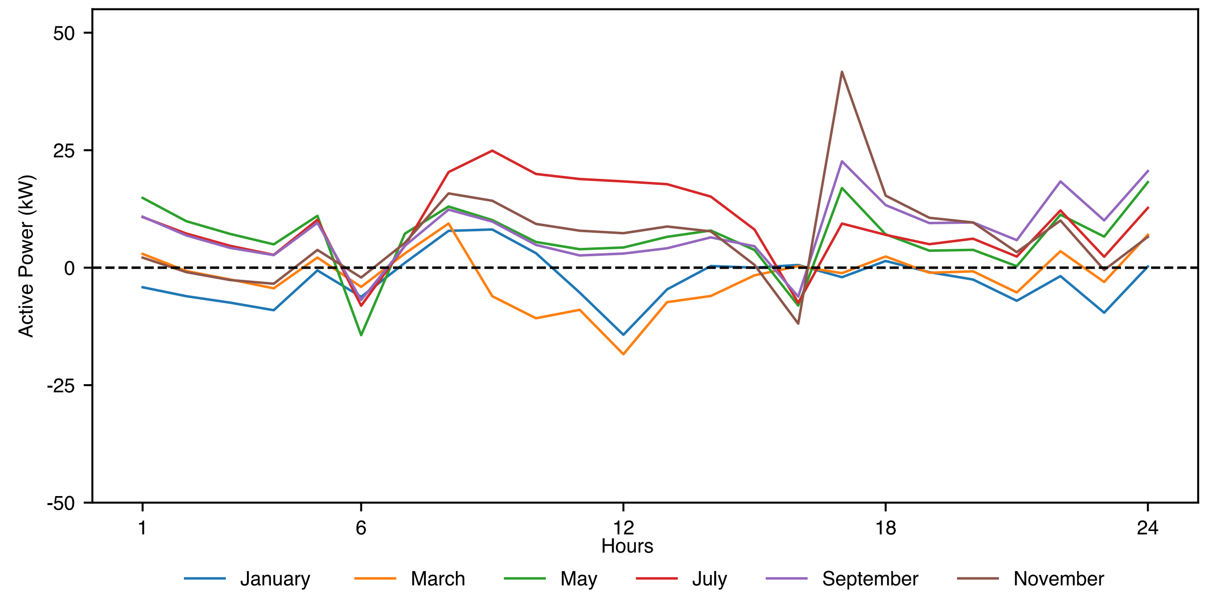
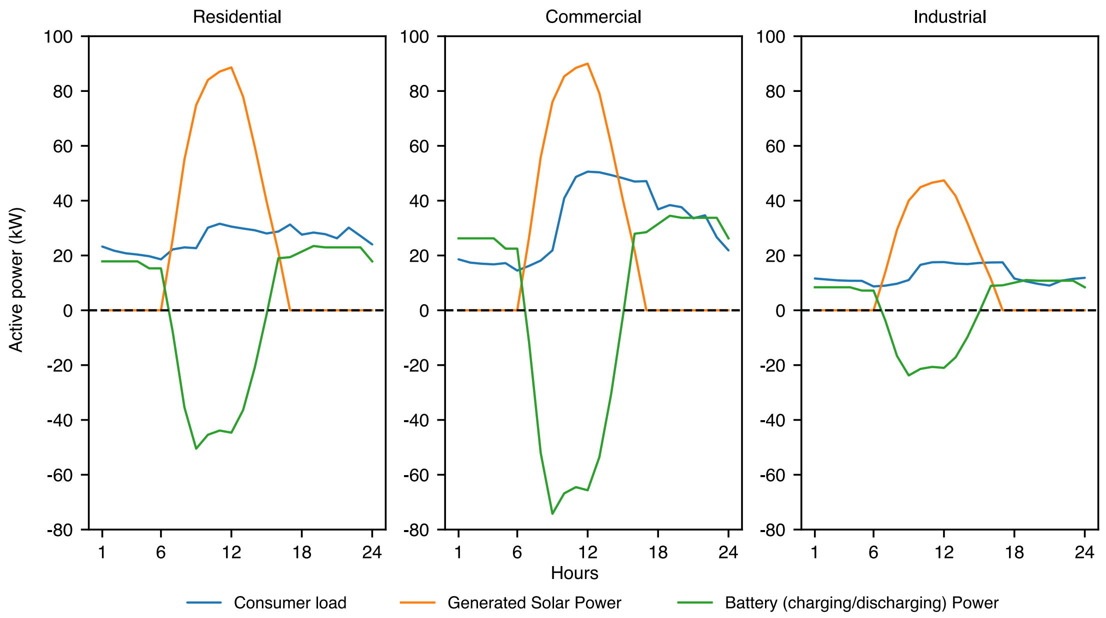


Figure 29: Active power imported beyond the DT for different months – Consumer Category with ToD tariffs and energy storage



Residential consumers and Industrial consumers connected to DT26 rely on grid energy supply and energy storage to serve their energy consumption during non-solar hours. For commercial consumers under DT26, energy stored is sufficient to serve all their energy needs during discharge hours from 22:00h to 06:00h (Refer to Figure 30).

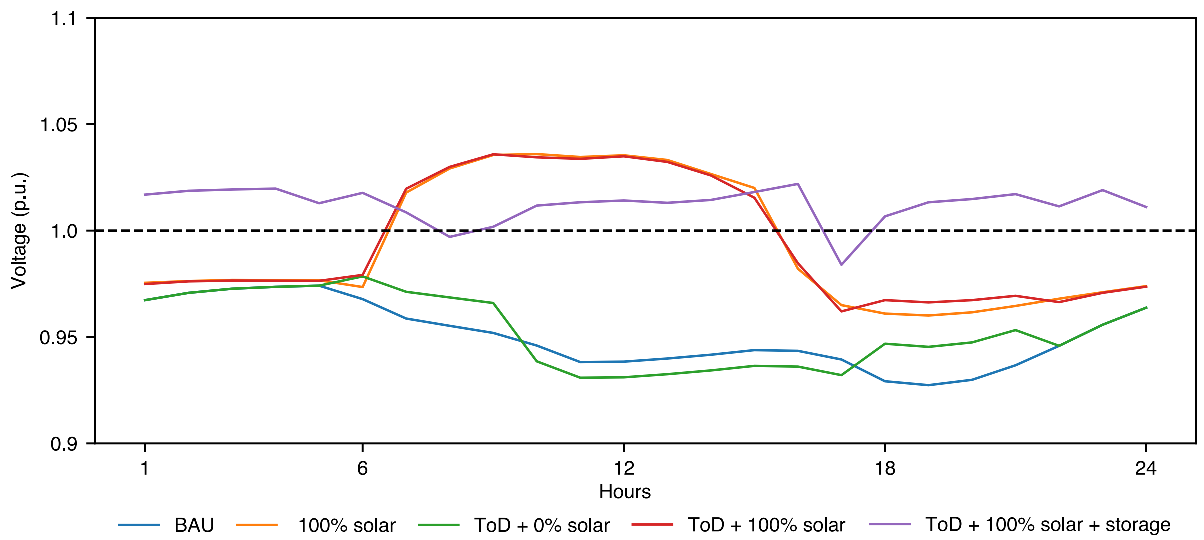
Figure 30: Active power of different consumers – Consumer Category with ToD tariffs storage



Voltage

A significant improvement in voltage profile can be observed with the introduction of energy storage. Most of the time, the voltage is near to 1 p.u. The BAU and BAU plus ToD tariffs scenarios show very low voltage profiles, compared to the voltage profile with 100% solar energy penetration plus ToD tariffs plus energy storage. For the 100% solar energy penetration scenario without storage systems, the voltage profile shows high fluctuations from solar hours to non-solar hours (Refer to Figure 31).

Figure 31: Comparison of voltages under different scenarios



A comparative analysis of the voltage ranges of all the service connection points with and without solar and storage energy systems is provided in Table 33. With the introduction of energy storage systems, it is evident that the voltages at different service connection points improved significantly during all the time slots. During the period 01:00h to 09:00h and 17:00h to 24:00h, voltages at majority of the service connection points are near to 1 p.u. During solar energy hours from 09:00h to 17:00h, the voltages at most of the service connection points are in the range of 0.98 – 1.06 p.u.

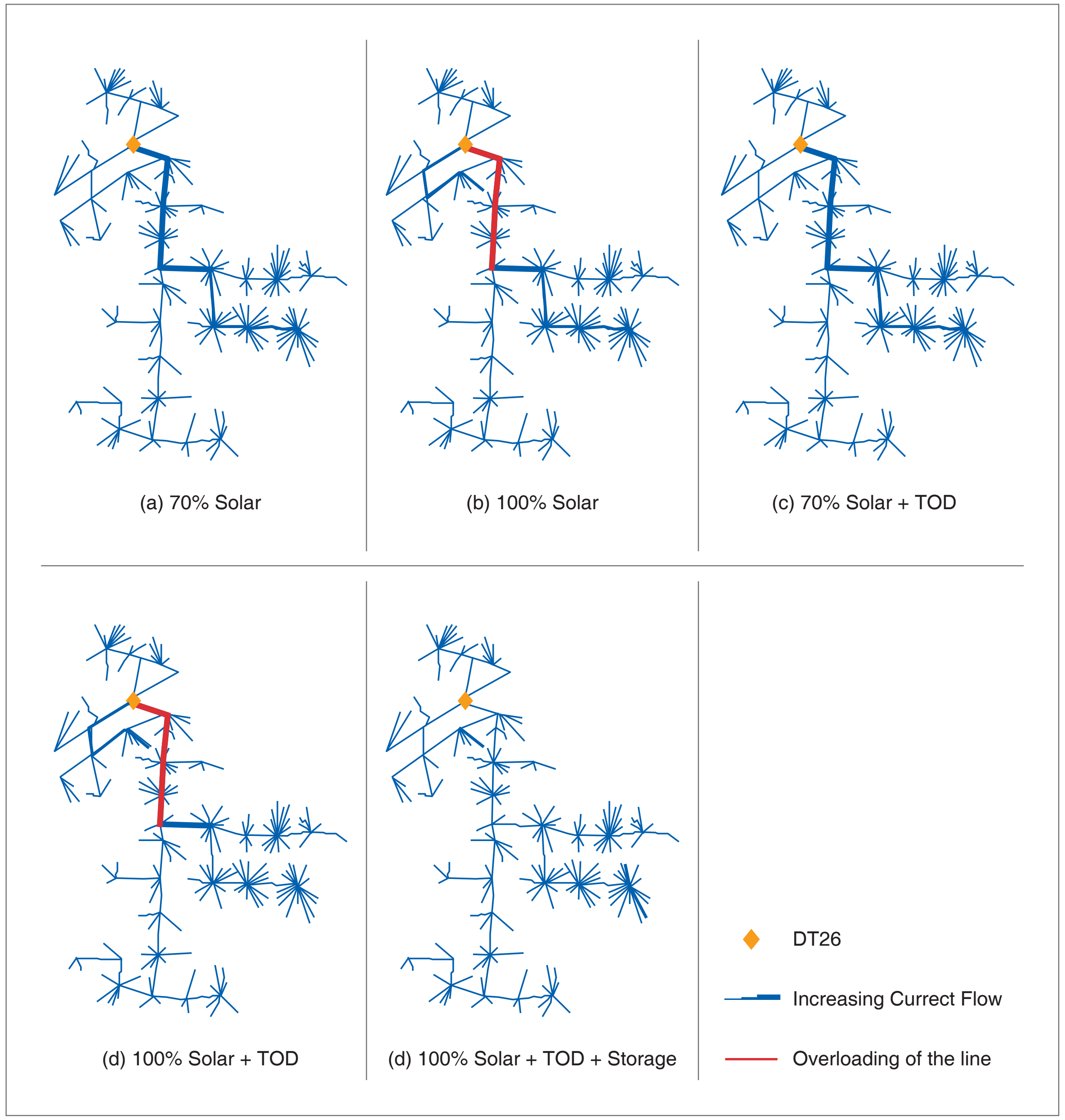
Table 33: Percentage of consumers in different voltage ranges with 100% solar penetration, ToD tariffs and storage

	01:00h - 9:00h				09:00h - 17:00h				17:00h-24:00h			
Voltage range (p.u)	**BAU**	**100%**	**ToD + 100%**	**ToD + 100% + storage**	**BAU**	**100%**	**ToD + 100%**	**ToD + 100% + storage**	**BAU**	**100%**	**ToD + 100%**	**ToD + 100% + storage**
0.9-0.94	0.26%	0.00%	0.00%	0.00%	5.15%	0.00%	0.00%	0.00%	29.59%	0.00%	0.00%	0.00%
0.94-0.98	65.21%	43.30%	40.65%	0.83%	66.75%	0.71%	0.71%	0.34%	43.96%	70.14%	71.11%	0.35%
0.98-1.02	34.54%	38.19%	38.94%	73.89%	28.11%	10.71%	11.48%	46.85%	26.46%	29.86%	28.89%	72.50%
1.02-1.06	0.00%	18.46%	20.36%	25.27%	0.00%	88.04%	87.31%	52.80%	0.00%	0.00%	0.00%	27.15%
> 1.06	0.00%	0.05%	0.05%	0.00%	0.00%	0.54%	0.50%	0.00%	0.00%	0.00%	0.00%	0.00%

Distribution Network Capacity:

The LT feeder current flow for DT26 was analyzed at 12:00h in November 2018. There is a substantial increase in energy flowing from solar generation point to DT26 for the 70% solar penetration level. For 100% solar penetration, the current carrying capacity is exceeded in both cases with and without ToD tariffs. However, with the introduction of ToD tariffs plus energy storage, overloading of LT feeders for the 100% solar penetration is avoided (refer to Figure 32).

Figure 32: Overloading of the lines under DT26 at 12:00h



Financial Analysis:

Initially, a solar plus storage feed-in tariff of INR 8.00 per kWh was assumed, given the fact that there is no currently solar plus storage tariff in place as of now. The value of INR 8.00 was assumed given it is similar to TANGEDCO's average CoS, even though the LCOS (Levelized Cost of Storage) for similar scale systems would be around INR 11.61 per kWh. There are no savings to TANGEDCO under the 100% solar penetration, ToD tariffs plus storage when compared to the BAU scenario. This is explained by: (i) increase in solar self-consumption, especially in high tariff consumers; and (ii) the higher cost of stored solar energy (Refer to Table 34).

Table 34: Consumer Category analysis 100% solar, ToD tariffs, plus storage

	BAU	100%	100% + ToD	100% + ToD + Storage
Solar Capacity Installed (kWp)	-	398.52	398.52	398.52
Solar Energy Produced (MU)	-	0.62	0.62	0.62
Storage Capacity (MWh)	-	-	-	4.96
Energy Stored/year (MU)	-	-	-	0.35
Grid Energy Metered @ DT	0.64	0.36	0.33	0.06
Distribution Losses (%)	3.02%	8.59%	8.53%	2.46%
Total CoS (INR Cr)	0.51	0.59	0.57	0.36
Revenue (INR Cr)	0.37	0.63	0.62	0.31
Net Revenue (INR Cr)	**(0.21)**	**(0.08)**	**0.05**	**(0.06)**
Savings over BAU Net Revenue[18](%)	**-**	**109.64%**	**111.17%**	**-15.73%**

The CoS of energy flowing downstream the DT26 (grid energy) decreases in the scenario with 100% solar energy penetration plus ToD tariffs plus energy storage when compared to the scenarios with 40% and 100% solar energy penetration plus ToD tariffs. The same happens for solar energy that is distributed within the DT26 network and solar energy that is supplied upstream the DT network (Refer to Table 35).

Table 35: CoS comparison per unit solar plus storage

	40%	100% + ToD	100% + ToD + Storage
CoS Grid Energy per kWh	**7.91**	**8.23**	**7.88**
CoS within DT Distribution Network per kWh Solar	**3.53**	**3.65**	**3.52**
CoS Beyond Feeder Distribution Network per kWh Solar	**3.64**	**3.77**	**3.63**
CoS Solar Plus Storage (within DT network)	**-**	**-**	**9.38**
CoS Solar Plus Storage (beyond DT network)	**-**	**-**	**9.77**

[18] For calculating the savings compared to the BAU scenario, the amount of energy supplied in the BAU is modified to match the energy supplied in the other scenarios.

Similar to the analysis performed for Utility Category solar, ToD tariffs plus storage in section 4.4, a 25 years analysis was conducted for the Consumer Category solar with ToD tariffs plus storage. Round-the-clock (RTC) energy tariff (solar plus storage) is kept constant. TANGEDCO's average PPC and fixed cost was assumed to grow by the rate of inflation. Savings for TANGEDCO are 93.82% compared to the BAU scenario. From year 11 onwards, revenue collection exceeds total CoS, resulting in net profits to TANGEDCO (Refer to Table 36).

Table 36: NPV solar penetration plus storage

	Value
BAU NPV (25 years) (INR Cr)	(1.56)
NPV 100% Solar Plus Storage Revenue (25 years) (INR Cr)	3.67
NPV CoS (25 years) (INR Cr)	(3.77)
100% Solar Penetration Plus Storage NPV (25 years) (INR Cr)	(0.10)
Net Revenue Present Value (%)	-2.62%
Savings over BAU Net Revenue 25 years (%)	**93.82%**
Revenue Exceeds Total CoS (Positive Net Revenue)	**From year 11 onwards**

A 25 years sensitivity analysis was conducted with a variable RTC feed-in tariff, starting at INR 4.00 per kWh up to INR 11.61 kWh. Savings to TANGEDCO are higher when RTC solar plus storage feed-in tariff is lower and for every increase in INR 0.50 in the RTC solar plus storage feed-in tariff there is a decrease of INR Cr 0.124 in savings. For a RTC feed-in tariff up to INR 7.50 per kWh, a positive net revenue can be observed over 25 years. When the RTC feed-in tariff is equal to the calculated LCOS of INR 11.61 per kWh as of June 2020, a 36.32% savings can be observed when compared to the BAU scenario over 25 years. As of June 2020, dedicated RTC feed-in tariff has not yet been determined by TNREC (Refer to Table 37).

Table 37: 25 years sensitivity Analysis on different LCOS

RTC solar + storage feed-in tariff	Net Revenue (% of Revenue)	Net Revenue NPV (25 year time series) INR Cr	NPV (25 year time series) savings BAU
4	24.38%	0.90	157.54%
6	10.88%	0.40	125.68%
8	-2.62%	(0.10)	93.82%
10	-16.00%	(0.59)	61.67%
11.61	-27.00%	(0.99)	36.32%

6. CONCLUSIONS

In the context of India's sustainability and renewable energy goals, this report presents policy-makers with a detailed evidenced-based analysis of a selected substation in Erode District, Tamil Nadu, and explores the technical and commercial impacts of different solar PV energy penetration levels at the distribution network. It assesses the benefits and challenges of integrating various levels of distributed solar energy generation at the distribution network level, and concludes that a distribution network with high solar energy penetration levels is technically and financially a viable proposition. The key findings below summarise each of the beneficial aspects of introducing solar into distribution networks.

6.1 Key Findings and Recommendations

For the Utility and Consumer categories of solar energy systems, scenarios with 40%, 70% and 100% solar energy penetration were simulated, with and without ToD tariffs. Additionally, a simulation with 100% solar energy penetration, ToD tariffs and solar energy storage was undertaken. The key findings are summarized below:

Distributed solar energy improves voltage profiles and reduces distribution losses

Voltage profiles show improvements for both the Utility Category solar and Consumer Category solar. Reduction in distribution losses is observed for both Utility and Consumer Category solar. At the same time an increase in distribution losses for the higher solar energy penetration levels can be observed as the total energy flowing back to the substation is increases.

Distributed generation is a good opportunity to improve voltage service levels

Voltage variations for HT levels and lower voltage levels maybe specified in the Regulations on Power Quality under the state's distribution standards of performance regulations. As per Indian Electricity Rules (Central Electricity Board, 2000) voltage variations up to ±6% are recommended for low and medium voltage at the point of commencement of supply. Other Indian states, such as Gujarat, Maharashtra, Andhra Pradesh, Madhya Pradesh, Delhi, also has a specified voltage variation up to ±6% as compared to Tamil Nadu, where it has a specified voltage variation of 6% above and 10% below the declared voltage (TNERC, 2013).

Recommendations:

- Adapt regulations for voltage variations that either meet CEA standards or go beyond it, as in other standards set by other States. In addition, include incentive and penalty[19] clauses for maintaining or violating these voltage standards in the Tamil Nadu Electricity Distribution Standards of Performance Regulations.

Existing infrastructure is able to take up high levels of solar penetration

With the 40% solar energy penetration scenario the maximum feeder current carrying capacity was not exceeded on all ten selected feeders. With a solar energy penetration level of 70%, feeder capacity was not exceeded in five out of ten feeders. The current carrying capacity of the low distribution network of DT26 is not exceeded with the 40% and 70% solar energy penetrations levels. With the 100% solar energy penetration scenario, in four out of the ten selected feeders the maximum feeder current capacity is not exceeded. For Consumer Category solar at the selected distribution transformers (DT26), a 100% solar energy penetration is only feasible if energy storage is added.

Recommendations:

- Conduct feeder-wise solar energy hosting studies to determine the optimal solar energy capacity requirement (technical and commercial).

[19] In the state regulation of Maharashtra and Andhra Pradesh, there is a provision for compensation to be paid by licensee for failing to maintain voltage variation limits (Forum of Regulators, 2018).

- Accelerate real-time metering at feeder level, DT level and the consumers service connection point, including agriculture, for the purpose of distribution and capacity addition planning.
- Publish maps that show the available grid-interconnection points along with optimal solar energy capacity to maximise benefits. Solar developers can utilize these maps in the planning of solar energy projects.
- Identify feeders with low average tail voltages and prioritize those for solarisation.
- Make distribution network data publicly available to stimulate research among academic and civil society organizations.
- Review existing data collection processes to ensure up-to date data is available for planning purposes.
- Consider deploying equipment, such as capacitor banks and DTs with automatic voltage regulation to improve voltage stability.

ToD tariffs facilitate higher local consumption of solar energy, reduce distribution losses and increase revenue

The introduction of solar energy in combination with ToD tariffs shows clear benefits. As some peak load is shifted to solar energy generation hours, local consumption of solar energy is maximised. When compared to the solar energy penetrations scenarios without ToD tariffs, all solar energy penetrations with ToD tariffs show lower technical losses, an improvement in the voltage profile, and a reduction in TANGEDCO's CoS. Further, introducing ToD tariffs results in a substantial revenue increase to TANGEDCO due to higher tariffs for energy consumption during the morning and evening peak hours (or other period selected for the higher ToD tariffs).

Recommendations:

- Petition for ToD tariffs for all consumer categories, this has both technical and financial benefits.

100% solar penetration with energy storage is a winning proposition

Our analysis illustrates that 100% solar energy penetration in combination with ToD tariffs and energy storage is a long-term winning proposition for both the Utility and Consumer Category solar scenarios. Along with improvements in the voltage profiles, there was also a reduction in distribution losses. No violations on current carrying capacity of the HT feeders or LT feeders are found.

Recommendations:

- Launch pilot projects that integrate solar energy and energy storage, as this is the most reliable way to assess the effectiveness of this strategy.
- Petition for dedicated solar plus energy storage tariffs for both, the Utility and the Consumer Category solar. This will incentives developers and consumer to deploy solar plus energy storage systems.

Solar energy as a CoS reduction strategy for TANGEDCO

All solar energy penetration level analyses show a reduction in TANGECO's CoS, for both the Utility and Consumer Category solar. CoS reduction for the Consumer Category solar are higher compared to the Utility Category solar, due to the very low net feed-in tariff for the Consumer Category. The flip side of this low net feed-in tariff is that there are very few consumers who install solar PV systems after the introduction of this tariff in March 2019.

Both Utility Category and Consumer Category solar systems have advantages and challenges and can be seen as complementary to each other and as essential parts of a sustainable energy future.

Table 38: Utility Category and Consumer Category solar comparison

	Utility Category	Consumer Category
Reduction on Grid Supply Dependency	↑	↑
Voltage Improvement	↑	↑
Reactive Power support	↑	↑
Losses Improvement	↑	→
Reduction in CoS	→	↑
Revenue Improvement	→	↑
Savings	→	↑

6.2. Limitations

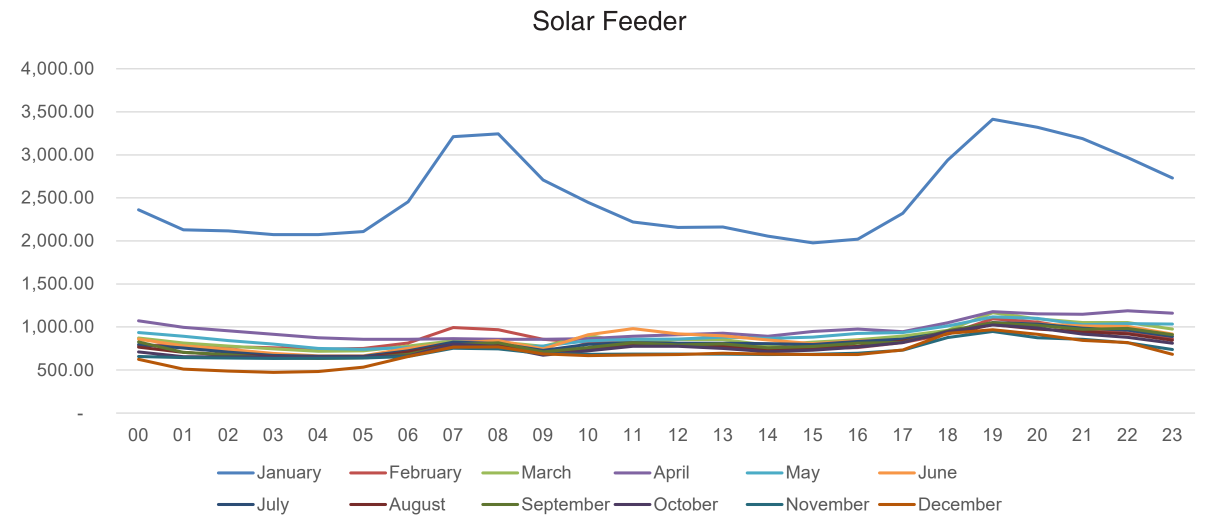
Even though there is voltage profile improvement for both the Utility Category solar and Consumer Category solar, relative distribution losses reduction is more evident under the Utility Category than under the Consumer Category solar. This may be due to the fact that the distribution network under DT26, on which the simulation for the Consumer Category solar was undertaken, showed no voltage limit violations and had low distribution losses even before the introduction of solar energy systems. Therefore, this finding may not be a representation for other distribution transformer networks with low voltage and high distribution loss issues in Tamil Nadu.

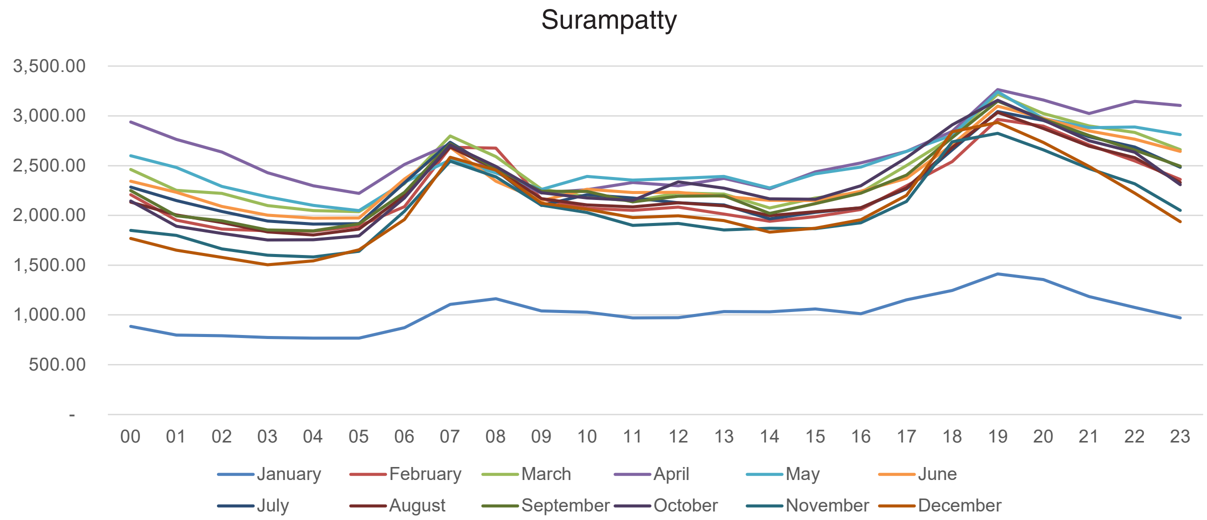
APPENDIX A - ASSUMPTIONS

Assumption	Unit	Values	Source/Reference
Costs			
Power Purchase Cost (PPC)	INR/kWh	5.81	Extrapolated for 19-20 from TANGEDCO P&L 17-18
Transmission Losses	%	8%	Tariff order 2017 pg. 47 paragraph 2.10.22
Distribution Losses	%	10%	Tariff order 2017 pg. 44 paragraph 2.10.12
Fixed Costs	INR/kWh	1.18	per TANGEDCO
CoS (Cost of Supply)	INR/kWh	8.04	per TANGEDCO
Billing Rate - Average	INR/kWh	5.83	per TANGEDCO
Billing Rate - Residential	INR/kWh	2.18	SS data
Billing Rate - Commercial	INR/kWh	9.77	SS data
Billing Rate - Industry	INR/kWh	5.11	SS data
Off-peak Tariff	INR/kWh	6.32	Pwc Report / 12th Capacity Building Workshop for officers of ERCs at IIT Kanpur
Normal Tariff	INR/kWh	6.65	Pwc Report / 12th Capacity Building Workshop for officers of ERCs at IIT Kanpur
Peak Tariff	INR/kWh	7.98	Pwc Report / 12th Capacity Building Workshop for officers of ERCs at IIT Kanpur
Solar Energy			
Solar Tariff	INR/kWh	3.04	Solar Tariff Order
Net-Feed-in	INR/kWh	2.28	Solar Tariff Order
LCOS – Utility Category	INR/kWh	6.97	SECI-2019-TN000012 Tender issued 01.08.2019
LCOS – Consumer Category	INR/kWh	8	Assumption
Solar Output per kWp/year	Wh	1584.3	PVWatts simulation
Days in a Year	days	365	-
Hours in a Day	hours	24	-
PV System Size – Consumer Category			
Residential	kWp	3	Assumption - based on Phase II grid connected rooftop program
Commercial	kWp	10	Assumption
Industry	kWp	25	Assumption
Financials			
Inflation	%	5.00%	Assumption
Annual Increase in CoS	%	2.00%	Assumption
Discount Factor	%	9.56%	Solar Tariff Order
Increase in Billing Rate	%	3.00%	Assumption
Annual Increase in Energy Consumption	%	0.00%	Assumption
Other Assumptions			
PV Plant CapEx	INR Cr/ MW	3.35	Solar Tariff Order
PV Land Requirement	Acre/MW	6.00	Solar Tariff Order

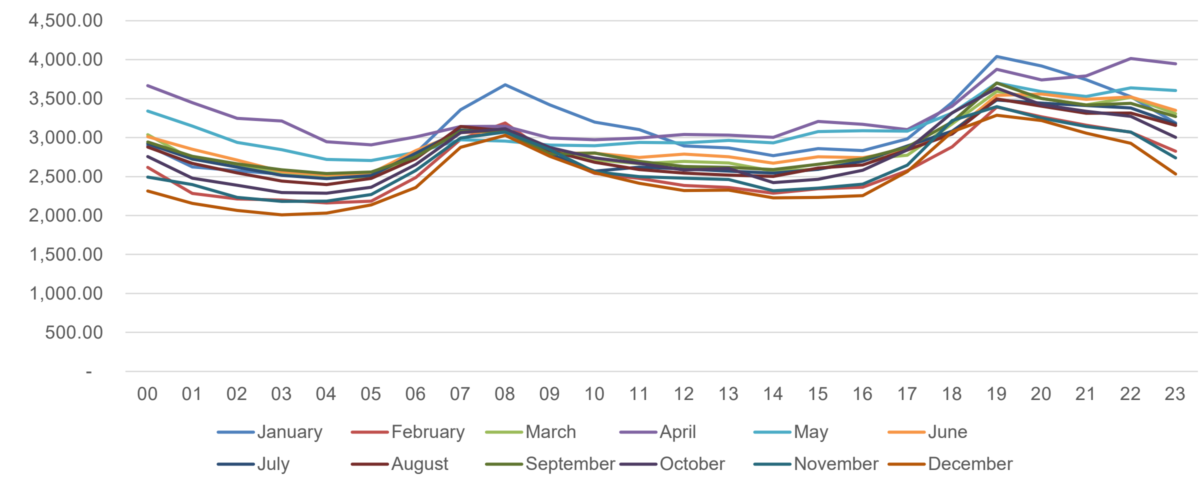
APPENDIX B – LOAD CURVES

FEEDERS LOAD CURVES

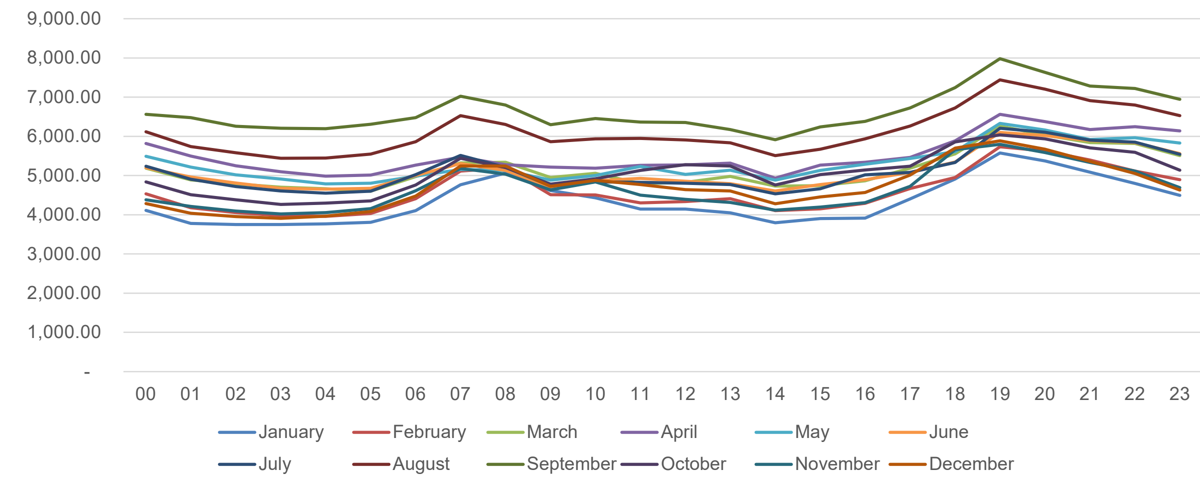




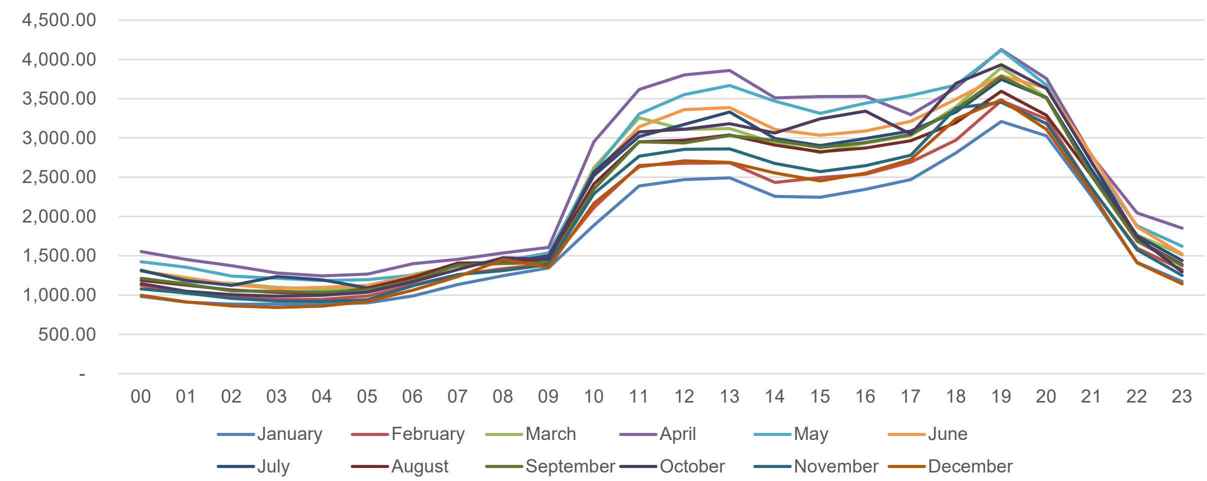
Southern Railway



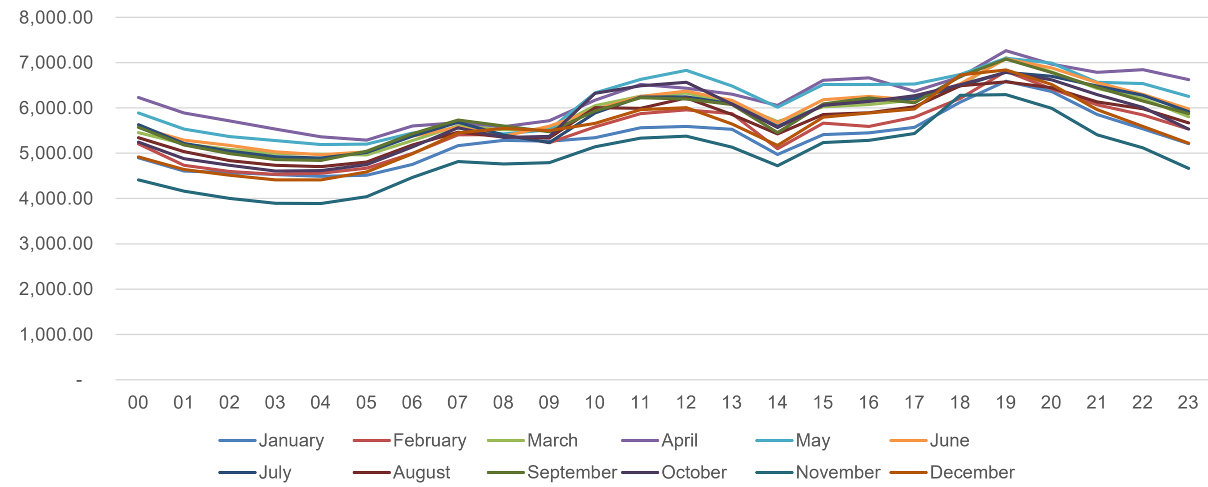
Karungalpalayam



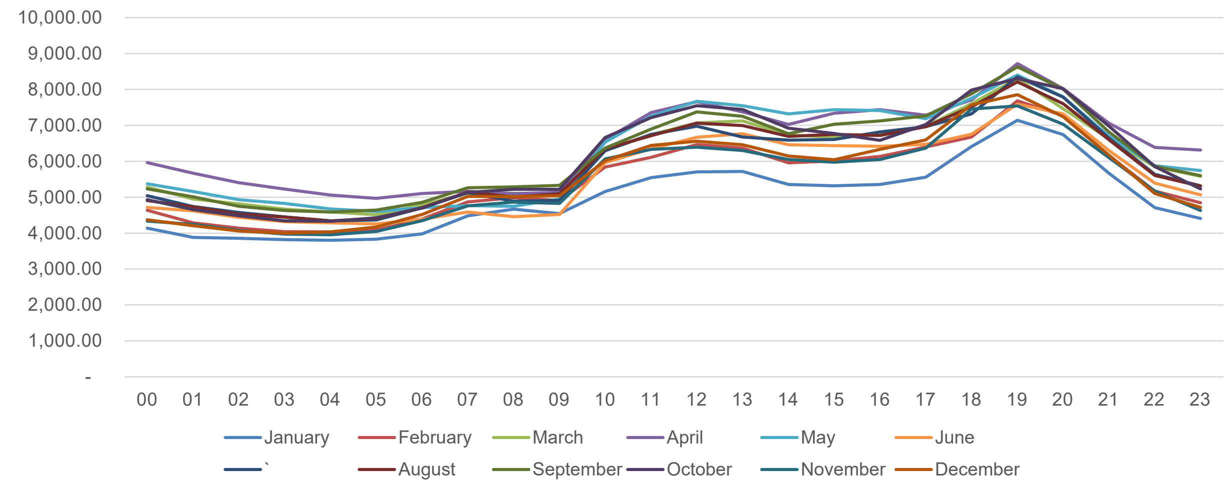
Erode Town



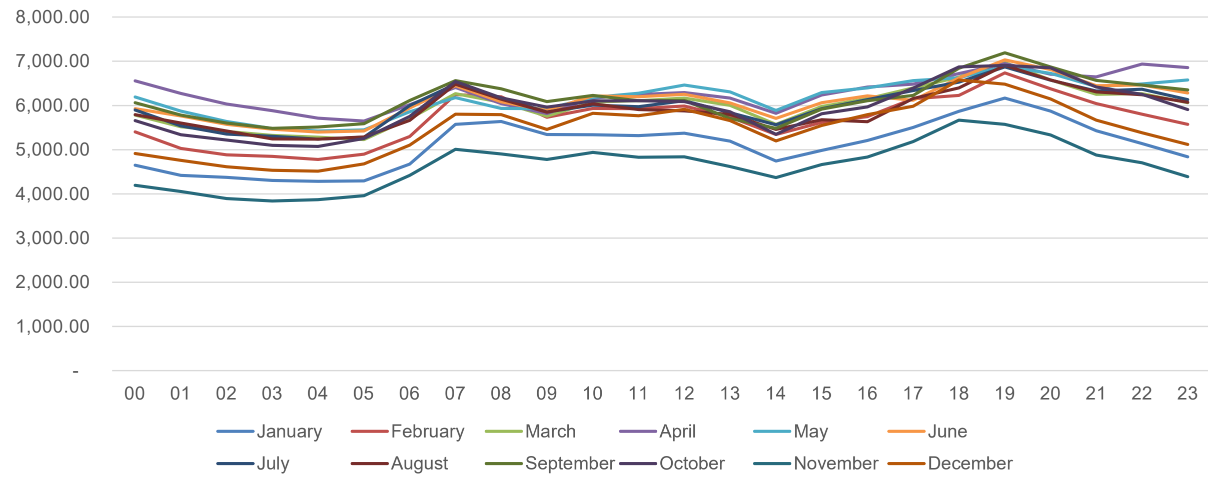
Ashokapuram



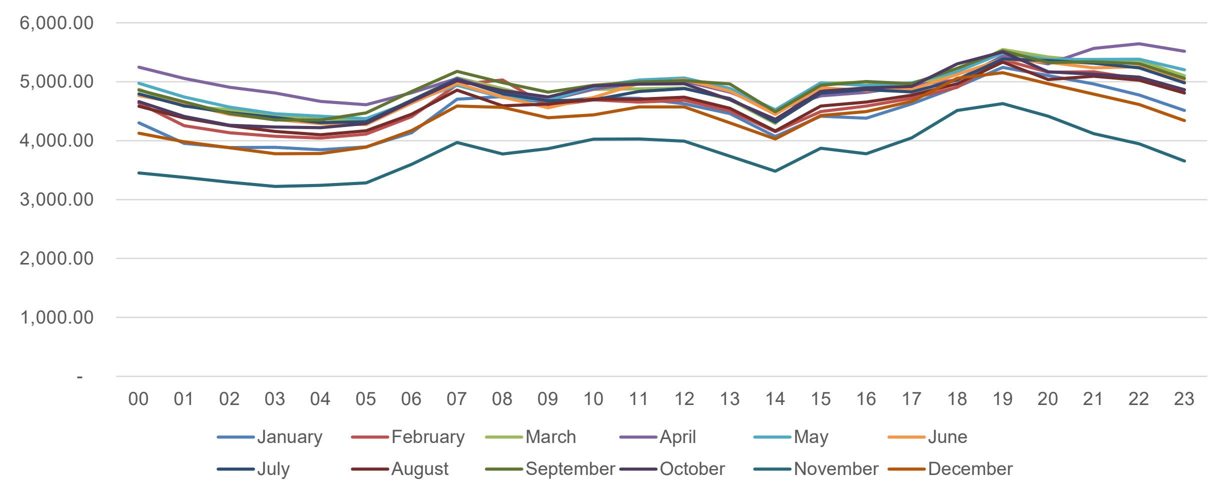
Market Feeder



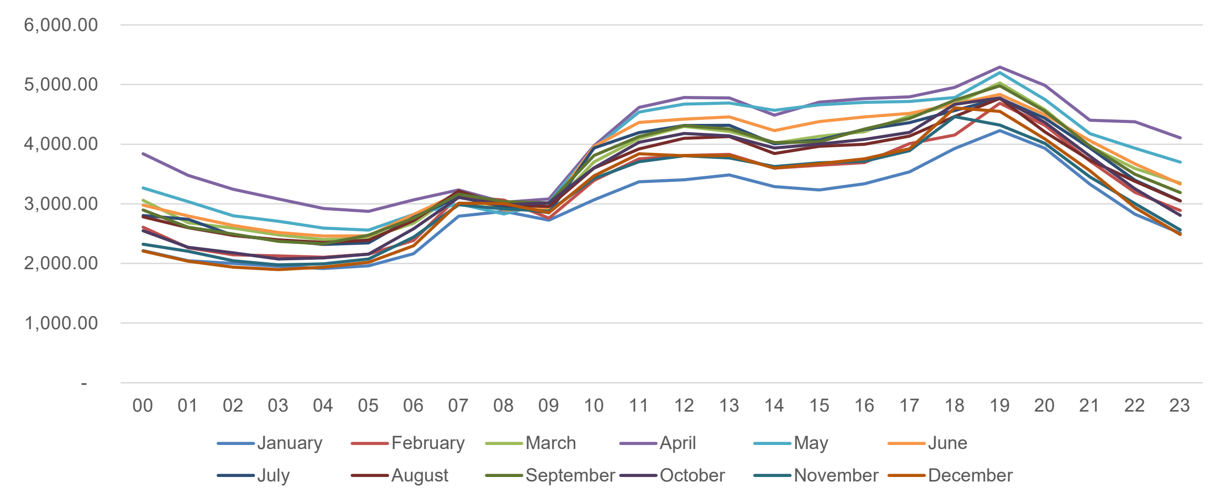
Narayanavalasu Feeder



Chathiram Feeder

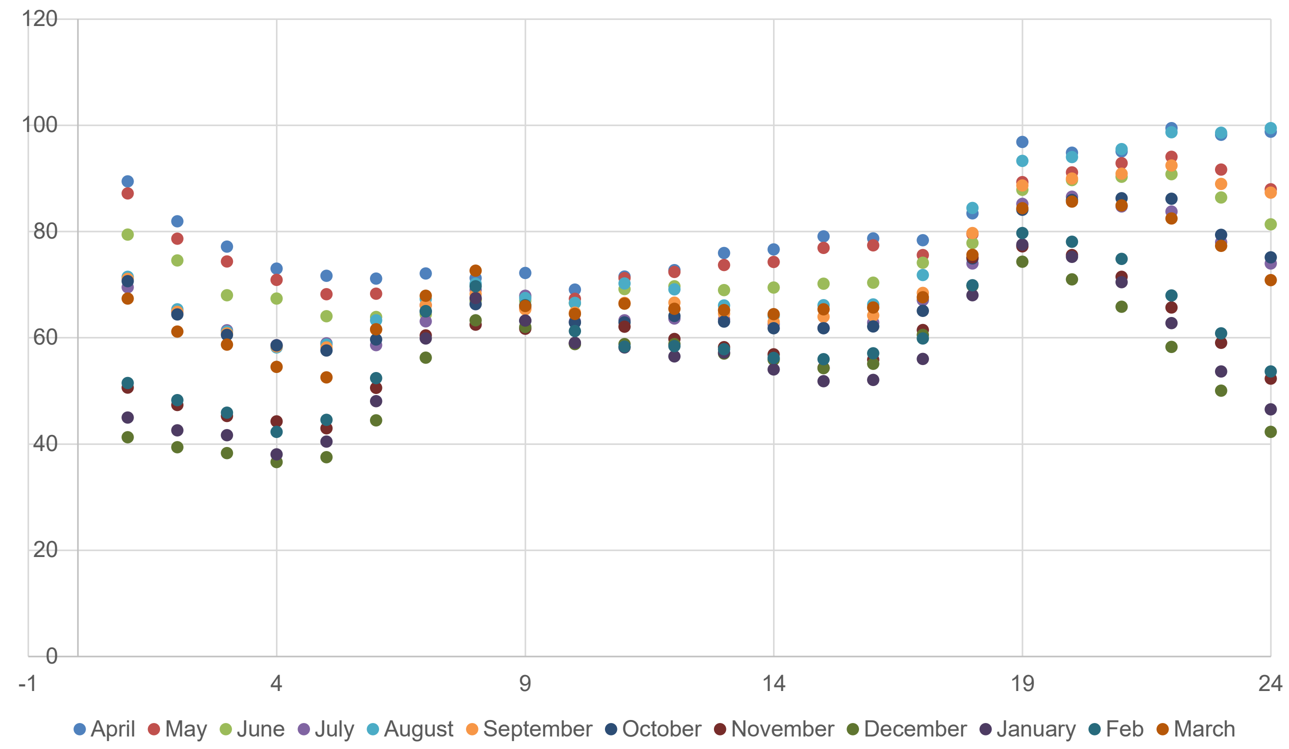


Collectrate Feeder

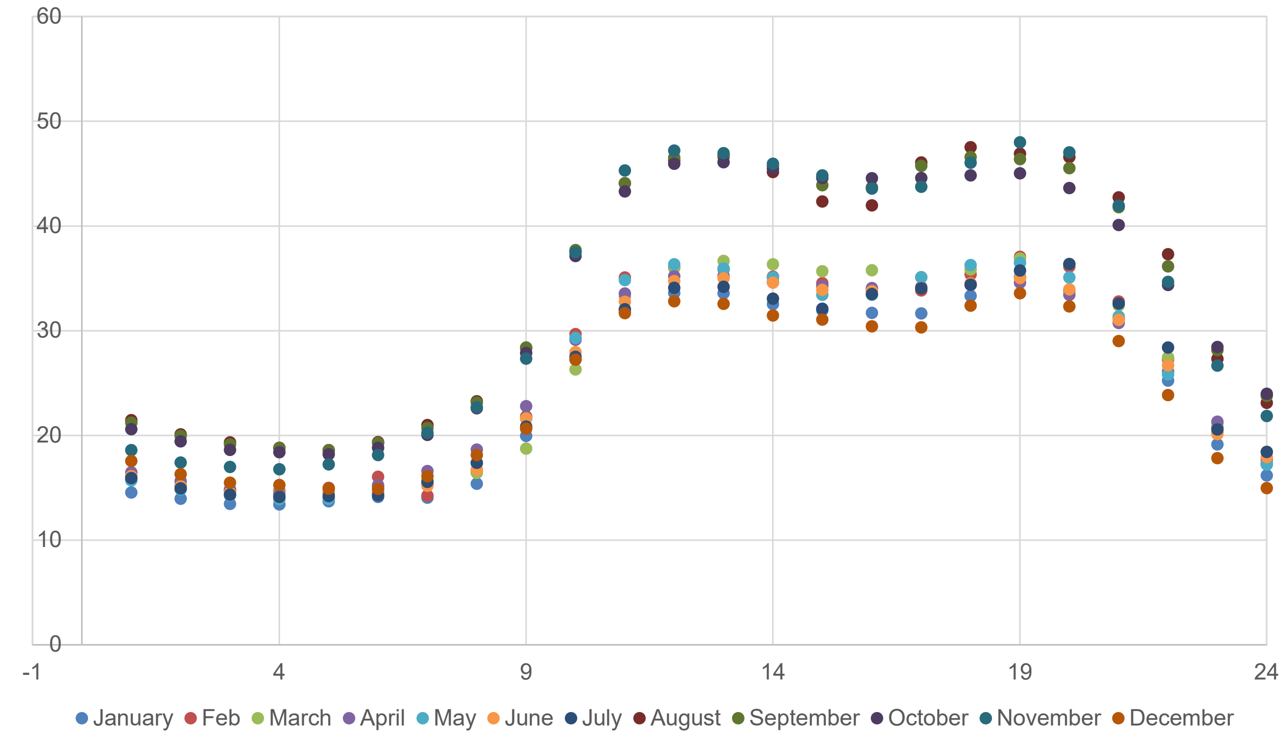


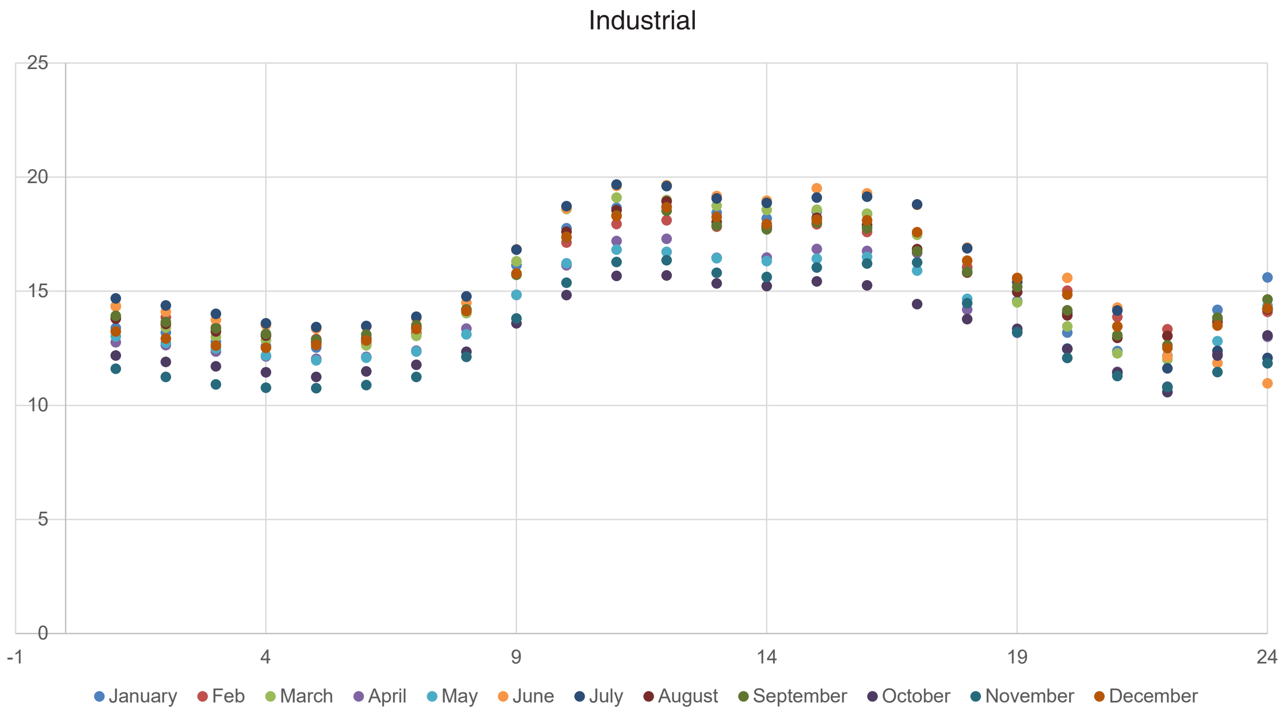
CONSUMER CATEGORIES LOAD CURVES

Residential



Commercial





APPENDIX C – SOLAR AND STORAGE SYSTEMS

The solar penetration levels were calculated based on actual energy consumption of the feeders for Utility Category and service connections under DT26 for the Consumer Category analysis. The following tables show the sizing of PV systems of each solar penetration level. The output of each kWp installed was defined as 1584.30 Wh of energy.

UTILITY CATEGORY

	40%		70%		100%	
Feeder Name	Solar Energy Capacity (MWp)	Solar Energy Produced (MWh)	Solar Energy Capacity (MWp)	Solar Energy Produced (MWh)	Solar Energy Capacity (MWp)	Solar Energy Produced (MWh)
Solar Feeder	2.14	3,399.24	3.74	5,948.67	5.34	30,174.34
Surampatty Feeder	4.89	7,782.06	8.56	13,618.61	12.23	40,917.42
Southern Railway Feeder	6.37	10,087.90	11.15	17,653.81	15.93	50,683.27
Erode Town Feeder	4.73	7,493.22	8.28	13,113.13	11.83	49,838.44
Market Feeder	12.89	20,413.87	22.56	35,724.31	32.23	45,528.63
Karungalpalayam Feeder	11.5	18,211.26	20.13	31,869.50	28.75	51,034.71
Ashokapuram Feeder	12.59	19,935.37	22.03	34,886.90	31.48	18,733.05
Narayanavalasu Feeder	12.8	20,273.21	22.41	35,478.19	32.01	25,219.74
Chatram Feeder	10.34	16,366.97	18.09	28,642.18	25.84	19,455.16
Collectrate Feeder	7.62	12,069.74	13.34	21,122.03	19.06	8,498.10
Total	85.88	136,032.84	150.28	238,057.32	214.69	340,082.86

CONSUMER CATEGORY

	40%		70%		100%	
Consumer Category	Solar Energy Capacity (kWp)	Solar Energy Produced (MWh)	Solar Energy Capacity (kWp)	Solar Energy Produced (MWh)	Solar Energy Capacity (kWp)	Solar Energy Produced (MWh)
Residential	62.38	96.76	109.15	169.35	155.94	241.93
Commercial	63.34	98.29	110.9	172.09	158.35	245.72
Industry	33.7	51.76	58.93	90.51	84.23	129.37
Total	159.42	246.81	278.98	431.95	398.52	617.02

STORAGE SYSTEM

	Market Feeder	Karungalpalayam Feeder	Residential	Commercial	Industry
Storage size (MWh)	95	102	0.001	0.005	0.008
Inverter (MVA)	15	15	0.001	0.005	0.008

APPENDIX D – NET RESULT FROM SIMULATION

UTILITY CATEGORY

ACTUAL LOAD (ALL FEEDERS)

Solar Penetration	PV Generation @ Generation point (MWh)	Surplus Solar Energy (MWh)	Energy Metered @ SS Level (MWh)	Losses (MWh)	Losses As Percentage Of Total Energy Supply (%)	Reactive Power Support From Grid (MVArh)
BAU	-	-	340,123.69	25,098.50	7.38%	168,551.70
40%	136,032.84	22,493.05	216,034.72	14,549.31	4.13%	127,156.59
70%	238,057.32	97,969.74	198,671.23	23,733.62	5.43%	151,347.67
100%	340,082.86	172,949.81	190,973.62	43,081.47	8.11%	192,512.23

TOD TARIFFS IMPLEMENTATION (ALL FEEDERS)

Solar Penetration	PV Generation @ Generation Point (MWh)	Surplus Solar Energy (MWh)	Energy Metered At SS Level (MWh)	Losses (MWh)	Losses As Percentage Of Total Energy Supply (%)	Reactive Power Support From Grid (MVArh)
BAU	-	-	329,517.68	23,886.50	7.25%	163,195.27
40%	136,032.84	18,890.53	201,446.03	12,957.16	4.42%	122,921.97
70%	238,057.32	94,204.36	183,242.74	21,464.52	5.09%	152,198.86
100%	340,082.86	170,153.95	175,990.44	40,288.17	7.81%	194,335.74

SOLAR PENETRATION + TOD TARIFFS + STORAGE (MARKET AND KARUNGALPALAYAM FEEDER)

	Market Feeder	Karungalpalayam Feeder
Stored Solar Energy Export Beyond SS (MWh)	5,150.95	6,259.81
Stored Solar Energy in Feeder Line (MWh)	20,852.01	19,729.18
Solar Energy to Feeder Line (MWh)	18,393.04	14,255.61
Grid Energy Supply (MWh)	7,398.51	5,821.73
Solar Energy Export Beyond SS (MWh)	732.08	1,380.33
Total Distribution Losses (MWh)	1,079.62	2,300.57

CONSUMER CATEGORY

ACTUAL LOAD (DT26)

Solar Penetration	Solar Energy Production	Net Grid Energy Support (MWh)	Net Solar Surplus Beyond Transformer (MWh)	Total Loss (MWh)	Total Loss (%) of Total Energy Input
BAU	-	642.81	-	19.41	3.02%
40%	246.81	408.83	11.12	21.12	3.22%
70%	431.95	370.37	135.86	43.07	5.37%
100%	617.02	355.38	265.51	83.51	8.59%

TOD TARIFFS IMPLEMENTATION

Solar Penetration	Solar energy production	Net Grid Energy Support (MWh)	Net Solar Surplus Beyond Transformer (MWh)	Total Loss (MWh)	Total Loss (%) of Total Energy Input
BAU	-	620.77	-	18.41	2.97%
40%	246.81	386.19	11.30	19.33	3.05%
70%	431.95	342.88	131.63	40.84	5.27%
100%	617.02	329.04	262.99	80.71	8.53%

SOLAR PENETRATION + TOD TARIFFS + STORAGE

	Total	Residential	Commercial	Industry
Total Solar Power Generated (MWh)	617.02	241.93	245.72	129.37
Total Battery Charging (MWh)	347.92	118.29	173.96	55.67
Total Battery Discharging (MWh)	303.76	103.28	151.88	48.60
Self-consumption Solar (MWh)	60.54	28.79	15.63	16.12
Self-consumption Solar Plus Storage (MWh)	53.57	34.42	8.23	10.93
Excess Solar Internal DT Loads (MWh)	208.56	90.58	63.12	54.86
Excess Solar Plus Storage Internal DT Loads	250.19	68.86	143.65	37.68
Total Surplus Energy (solar plus storage) (MWh)	14.08	-	-	-
Total Solar Surplus (MWh)	8.18	-	-	-
Total Battery Surplus (MWh)	5.9	-	-	-
Total Grid Support (MWh)	56.25	-	-	-
Excess Solar Export DT Loads (MWh)	11.52	-	-	-
Excess Solar Plus Storage Export DT Loads (MWh)	7.44	-	-	-
Battery (MWh) Loss	44.16	-	-	-

APPENDIX E – TIME-OF-THE-DAY TARIFFS

Calculations for ToD tariffs were based on the Assignment on Implementation & Impact Analysis of Time-of-the-Day Tariff in India (PriceWaterhouseCoopers, 2010) report.

Assumptions

Times slots and Billing surcharge plus rebate
The time slots adopted for this report are the same applied to HT consumer in Tamil Nadu as per Tariff Order 2017 (TNREC, 2017), which are the following: Peak times from 6:00h to 9:00h and 18:00h to 21:00h. Off-peak times are defined from 10:00h to 5:00h. Normal hours are from 10:00h to 16:00h. According to the tariff order, a 20% surcharge was applied to peak times and a 5% rebate was applied to off-peak times.

Peak shifting
For estimating the impact of ToD tariffs on the load curve, it was assumed that a 1% increase in tariff rate translates into a 1% of demand reduction. Therefore with a peak tariff increase of 20% over the normal tariff electricity consumption during peak demand hours has been reduced by 20%. 50% of this reduction is assumed to be shifted to normal demand hours and was distributed evenly. The remaining 50% is assumed to be avoided consumption.

Methodology

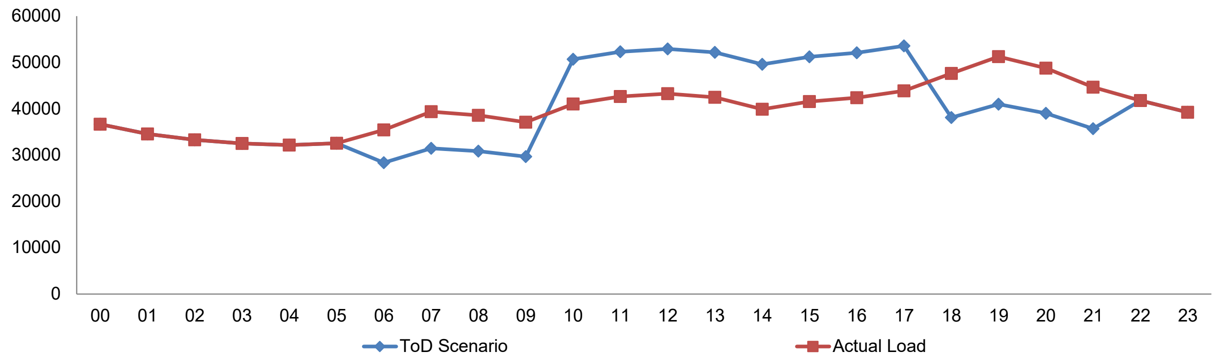
For calculating the load shift from BAU to a new scenario where ToD tariffs are implemented, the following methodology was adopted:

Step 1: Create a pivot table in Excel with all the yearly loads. Associate every hour of the day with the ToD time slot (peak, off-peak and normal).
Step 2: Sum up by day the total load occurring during peak times
Step 3: Create an average peak load, by dividing the sum of total load during the peak time by the total number of peak hours:

$$\text{Average Peak Load (hourly)} = \frac{\text{(Total peak load (daily))}}{\text{(\# peak hours per day)}}$$

Step 4: Reduce by 20% of all load during peak times in a daily basis.
Step 5: Multiply by 10% the average peak load and add to all normal hours in a given day.
Step 6: Repeat the procedure for the entire database (365 days).

Figure 33: Yearly average load after ToD tariffs implementation



APPENDIX F – FINANCIAL CALCULATIONS

Equations used to calculate CoS from different energy sources:

CoS Grid Energy
Cost of supply grid energy=PPC+FC×(PPC×DL+PPC×TL)

CoS Solar Feed-in
Cost of solar feed in= Solar Tariff+FC+(Solar Tariff×DL)

CoS Export Solar
Cost of solar export= Solar Tariff+FC+(Solar Tariff×DL+Solar Tariff×TL)

CoS Solar + Storage within DT network
Cost of solar+storage= LCOS+FC+(LCOS×DL)

CoS Solar + Storage export
Cost of solar+storage export= LCOS+FC+(LCOS×DL+LCOS×TL)

Where:
PPC = Power purchase cost, LCOS = Levelized Cost of Storage, FC = Fixed costs, DL = Distribution Losses, TL = Transmission Losses

APPENDIX G – SIMULATION PROCEDURE

Utility Category

BAU Case:

Step 1: Define all the power system elements like source, lines, load, and transformer in OpenDSS software as per our system data. Also define general information like load shapes, line codes.

Step 2: Define all monitors and energy meters to read voltage and power

Step 3: Using python interface, run the power flow for the OpenDSS model for one year and save all the monitor data in the specified folder

Step 4: Calculate the total power, feeder voltages and distribution losses of the 10 feeders.

Step 5: Plot the required parameters Vs hours for different analysis

Different Solar Energy Penetrations:

Step 6: same as step 1 of BAU case

Step 7: Define PV systems and inverter control in OpenDSS for the 10 feeders. Also define the monitors to read the voltage and power from the PV systems

Step 8: Using python, create a loop to run the power flow of the OpenDSS model for 40%, 70% and 100% penetration and save all the monitor data in the respective folders

Step 9: Calculate the total line power, solar power, feeder voltages, and distribution losses of the 10 feeders.

Step 10: Plot the desired parameters using python interface.

ToD Case:

Step 11: Redefine the loads of step 1 of BAU scenario with ToD tariffs.

Step 12: Repeat steps 3 to 10.

With Energy Storage:

Step 13: Calculate the storage system size to store the surplus solar energy going beyond the substation for the selected Feeder.

Step 14: Define the storage element and the monitors for storage elements for the selected Feeder in OpenDSS

Step 15: Run the load flow using python interface and save the results in the desired folder

Step 16: Calculate the total line power, solar power, battery power, feeder voltages, and distribution losses of the selected feeders.

Step 17: Plot the desired graphs using python interface for different analysis.

Consumer Category

BAU Case:

Step 1: Extract the data of the selected DT from QGIS file to an excel file.

Step 2: Define all the power system elements like source, lines, load under each consumer category, and transformer in OpenDSS software using python interface. Also define general information like load shapes, line codes.

Step 3: Define all monitors and energy meters to read voltage and power

Step 4: Using python interface, run the power flow for the OpenDSS model for one year and save all the monitor data in the specified folder

Step 5: Calculate the total line power, voltages at each service connection points and distribution losses in the DT network.

Step 6: Plot the desired parameters Vs hours for different analysis.

Different Solar Energy Penetration:

Step 7: Same as step 2 in consumer category of BAU case

Step 8: Set the solar penetration as 40%. Find the number of consumers need to be solarized based on the energy consumption for the desired penetration.

Step 9: Define PV systems and inverter control in OpenDSS using python interface. Also define the monitors to read the voltage and power from the PV systems

Step 10: Run the power flow in OpenDSS using python interface platform and save all the monitor data in the result folder for the selected solar penetration.

Step 11: Repeat the step 7 to 9 (in Consumer Category) for 70% and 100% penetration.

Step 12: Calculate the total line power, solar power, voltage at each service connection points and distribution losses under the selected DT for all the solar energy penetrations.

Step 13: Plot the desired graphs for the desired hours

With ToD Case:

Step 14: Redefine the loads of step 1 with ToD tariffs

Step 15: Repeat steps 2 to 13 (of Consumer Category) for the new loads with ToD tariffs

With Storage:

Step 13: Calculate the storage system size for different consumer category for 100% solar penetration with ToD tariffs scenario to store the surplus solar energy.

Step 14: Define the storage elements and monitors for storage elements in OpenDSS using python interface.

Step 15: Run the load flow using python interface and save the results in the desired folder

Step 16: Calculate the total line power, solar power, battery power, voltage at each service connection points, distribution losses under the selected DT.

Step 17: Plot the desired graphs using python interface for different analysis.

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