SPV GRID PENETRATION STUDY

Effect of increasing Solar PV grid penetration on voltage and bidirectional energy flow on the low tension side of the Distribution Transformer

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Introduction

ACKNOWLEDGMENT

We wish to thank the World Resources Institute for sponsoring this field study. We also express our gratitude to Auroville Electrical Service, Sunlit Future and Cynergy (units of the Auroville Foundation) for their expertise and technical support on the field. We also thank the building stewards and staff at Matrimandir, Town Hall, the Auroville Foundation Office, Sri Aurobindo International institute for Educational research (SAIIER) and Maroma for allowing their respective Solar Photo-voltaic (SPV) systems to be part of this study.

ABSTRACT

Electricity regulatory commissions of different states have set different limits for the maximum level of solar energy grid penetration on the low tension (LT) side of the distribution transformer. In Tamil Nadu this limit has been set at 30% of the rated capacity of the distribution transformer.

The purpose of this study is to monitor and evaluate the technical implications, if any, of crossing this limit. The technical parameters that are monitored are voltage at various locations in the LT network, and bidirectional energy flow (active and reactive) on the LT side of the distribution transformer.

When solar photo-voltaic (SPV) systems are turned on, there is a reduction in the import of active energy from the grid. This results in a reduction of the instantaneous load (instantaneous active power import) which in turn reduces the demand on the distribution transformer (DT).

The solar PV penetration level which was tested in this field study ranges from "0 – 20%" of the distribution transformer capacity. The tests carried out show that voltage across the low-tension terminals of the distribution transformer increases marginally (≤ 1.12%) when SPV is on. The phase to neutral voltage at the LT terminals of the transformer remained within a range of 230V +/-9%. It should be noted that the change in voltage cannot be entirely attributed to the solar PV energy penetration as there would be other factors such as load changes that also have an impact on the voltage. Bi-directional energy flow analysis shows that there was zero or near zero active energy evacuation to the HT side of the transformer, and only on certain holidays when there was no consumption load. There was no reactive energy export to the HT side of the distribution transformer.

INTRODUCTION

The Government of India has set a target of 100,000 MW of solar energy by 2022. Of this target, 40% is earmarked for the small scale consumer (rooftop) segment. The majority of these electricity consumer systems will have a net-metering facility whereby energy exported to the grid is deducted from imported energy to arrive at the net energy to be paid for. In these solar PV systems the energy that is generated is consumed by the electrical loads of the building with the surplus energy, if any, flowing into the grid and the deficit being taken from the grid.

The Central Electricity Authority (CEA) published Technical Standards for Connectivity of Distributed Generation Resources Regulations in 2013[2]. These regulations deal with issues such as harmonics, DC current injection limits and various safety requirements for grid connected renewable energy generators. The above mentioned CEA regulations do not prescribe a grid penetration limit of renewable energy generators.

Over the years, grid connected solar installations have increased in size and number. In 2015, India doubled its total grid connected SPV capacity[10]. The uptake of grid connected solar is experiencing exponential growth, and this has led state and national regulatory bodies to introduce guidelines and limits for SPV installations. One of the limits pertain to the total SPV capacity that can be connected on the low tension side of the distribution transformer level.

The Tamil Nadu Electricity Regulatory Commission (TNERC) has capped the total solar PV capacity at distribution transformer level at 30% of the distribution transformer capacity (e.g. a 100 KVA distribution transformer can have a total of 30 kW of SPV capacity connected to the electrical service connections of consumers connected to that transformer). The regulation reads as follows:

“The Nodal officer shall accord solar net metering approvals on a first come first served basis until the grid connected Solar PV installed capacity reaches 30% of the closest upstream Distribution Transformer rated capacity.”[17]

In Tamil Nadu, the SPV capacity has also been capped at the contracted load for each individual service connection level.[19]

The states of Rajasthan[16], Gujarat[5] and Kerala have also set SPV penetration levels. Karnataka has not set a limit for SPV capacity at distribution transformer level, but has capped the SPV capacity at service connection level (to not exceed the sanctioned load)[7].

The primary objective of this study is to determine the technical implications (if any) of increasing SPV grid penetration on the low tension side of the distribution transformer, including tail ends of the LT feeders in a given distribution network, by measuring voltage, current and bi-directional energy flow.

LITERATURE REVIEW

A literature review was undertaken to understand other research studies in the field of grid penetration.

Patel (2015)[14] reports that simulations show a higher grid penetration of SPV for a given distribution transformer improves the voltage profile of the grid, reduces import of power from the substation and thereby decreases transmission losses. Although Patel does not comment on the effect of reverse power flow for high SPV penetrations (of greater than 50%), the report recommends SPV installation from the tail-end of a feeder.

A study by Deloitte (2014)[15] compiles technical and commercial issues with respect to high SPV penetration which are slowing the uptake of solar energy. This includes issues relating to reverse power flow in a low tension network and losses to the distribution licensee due to reduced power import from consumers. This study also recommends installing SPV from the tail-end of the feeder, which will reduce distribution losses and also enhance the stability of the grid. The study also suggests using smart inverters for reactive power management, intelligent substations and auto-tap changing in distribution transformers for accommodating higher SPV grid penetration.

Fechner et al. (2009)[3] argue that the hierarchical topology of the grid was designed for unidirectional power flows and explore inverter technologies to mitigate these issues. Fechner recommends inverters with grid management capabilities, as these will stabilize the grid in the event of a failure of several SPV systems. The authors stress the need for standards and regulations that support penetration of distributed generation.

Several studies address infrastructure related costs resulting from high SPV penetration. Eric (2013)[22] studies the impacts of high wind and solar energy penetration and concludes that for the grid under study, the cost of conventional fuel power stations with renewables are lower than the monetized reduction in carbon emissions. The study comes with a clear disclaimer that the results may apply only to the grid studied. Lilienthal[8] suggests the use of bulk energy storage systems for storing any excess energy generated from distributed generation during periods of peak resource availability, in order to eliminate the need for cycling with conventional energy based power plants. Boris Schucht, CEO of a major transmission operator in Germany, has expressed confidence that electricity grids can withstand very high penetrations of wind and solar energy of up to 70% before additional energy storage will be required[13].

GE and Arizona Public Service Utility studied the effect of high solar energy penetration on the grid, using detailed load modeling and advanced metering infrastructure. The team simulated high penetration ratios on a representative feeder using weather data at 1-second intervals and electrical data acquisition systems[11].

The study found that there were no SPV penetration standards that could be readily applied to different feeders, since this was dependent on local characteristics of the feeder. An SPV penetration level that was operationally acceptable on one feeder could raise safety concerns on a different feeder. Hence, the study recommends modeling tools in order to evaluate systems and feeders on a case-by-case basis. The study also found the need for data collection to be done at a sufficiently high resolution in order to adequately represent the system. Lastly, this study found the need for smart inverters in grids with higher SPV grid penetration, as they can be remotely controlled and monitored[12].

Picture 1 - Auroville Foundation SPV Plant (Auroville, India)

Picture 2 - Town Hall SPV Plant (Auroville, India)

The Matrimandir Distribution Transformer

EXPERIMENT DESIGN AND METHODOLOGY

Based on the preceding literature review, this study was designed as a two-stage experiment. In Stage 1, data was collected passively by meters installed and programmed for the purpose, with no other active intervention in the chosen sites. The data collected was used to compare voltage and bidirectional energy flow between day time (when solar energy was being produced) and at night time (in the absence of solar). This data was used to determine the health of the system, identify any scenarios or issues that affect the normal functioning of the system (for example, whether there is a voltage increase beyond acceptable limits) and to predict system behaviour beyond currently set limits.

Since the energy load profile is significantly different between day and night, Stage 2 of the experiment attempted to evaluate the impact of solar energy by accounting for differences in load. A 2-hour time slot on regular working days was identified, and SPV was turned OFF on certain days, and kept ON on other days. Data collected in these time slots was used to compare voltage and bidirectional energy flow, with and without SPV.

Thereafter, SPV systems were turned off at predetermined time periods, and the same data (voltage, current, and bidirectional energy flow) during these times were compared with measurements taken in similar time periods with SPV turned back on.

Data collected on weekends, holidays, and times other than the 2-hour study time slot was not taken for analysis. Errors and inconsistencies in data collected were removed using a data clean-up process as detailed in Annex 4 and Annex 5 before being used for analysis.

This study uses 2 types of data analyses.
1. Daily Average Analysis which calculates the average values for each time of the day, for a 24-hour period

2. Monthly Average Analysis which compares monthly averages of voltage and bidirectional energy flow over the course of the study

The scope of this study is limited to observing the technical implications of increasing SPV grid penetration on voltage and bidirectional energy flow only on the low-tension side of the distribution transformer. Effects of SPV on the high-tension side of the distribution transformer, as well as reasons for the observed effects are beyond the scope of this study.

Two distribution transformers in Auroville (Villupuram district, Tamil Nadu) with a relatively high percentage of grid connected solar photo-voltaic (SPV) systems were selected for the study

1. Matrimandir distribution transformer
2. Maroma distribution transformer

The field study and findings at each Distribution Transformer are presented below.

1. MATRIMANDIR DISTRIBUTION TRANSFORMER

The Matrimandir LT distribution grid supplies power to a mix of household, office building and industrial loads at the center of Auroville. The load buildings in this network were also equipped with bidirectional meters to get a better picture of power supply characteristics. It has 50 kWp of grid connected SPV (distributed over 4 grid connected installations) and a 250 KVA 3-phase transformer (22KV / 415V) with an On Load Tap Changer (OLTC) supplying power to a combination of residential, office and industrial (workshop) building loads.

This distribution network, including the incoming 22 KV HT cable, the 250 KVA 22KV / 415V transformer and the entire LT distribution system, is Auroville-owned. There is an interconnection with the TNEB grid at a voltage level of 22KV through an HT service connection. The Matrimandir (LT) network therefore functions as a micro (or mini) grid with connectivity to the public grid. All measurements relating to this study were carried out on the LT side of the system.

The main electrical load in this network belongs to Matrimandir, the building in the center of Auroville, known as the “Soul of Auroville”. Loads at Matrimandir comprise of lights, pumps, workshop equipment and air-conditioning. When all SPV installations are switched ON, this network has a peak SPV capacity of 50 kWp which results in a maximum grid penetration ratio of 20% of the distribution transformer capacity.

Building / Cluster name	Connected load (kVA)	Solar PV Capacity (kW)
Matrimandir	116.1	15
Town Hall	32.2	10
Auroville Foundation Office	21.48	15
Office of Sri Aurobindo International Institute of Educational Research (SAIIER)	4.24	10
Sankshipt (residential, industrial/workshop)	7.04	0
Citadines (residential building)	31.37	0
Mitra Youth Hostel (residential building)	6.06	0
Inspiration (residential building)	22.34	0
Manoj (residential building)	0.41	0
Total	**241.24**	**50**

Table 1: Loads and installed grid connected SPV in Matrimandir LT distribution network

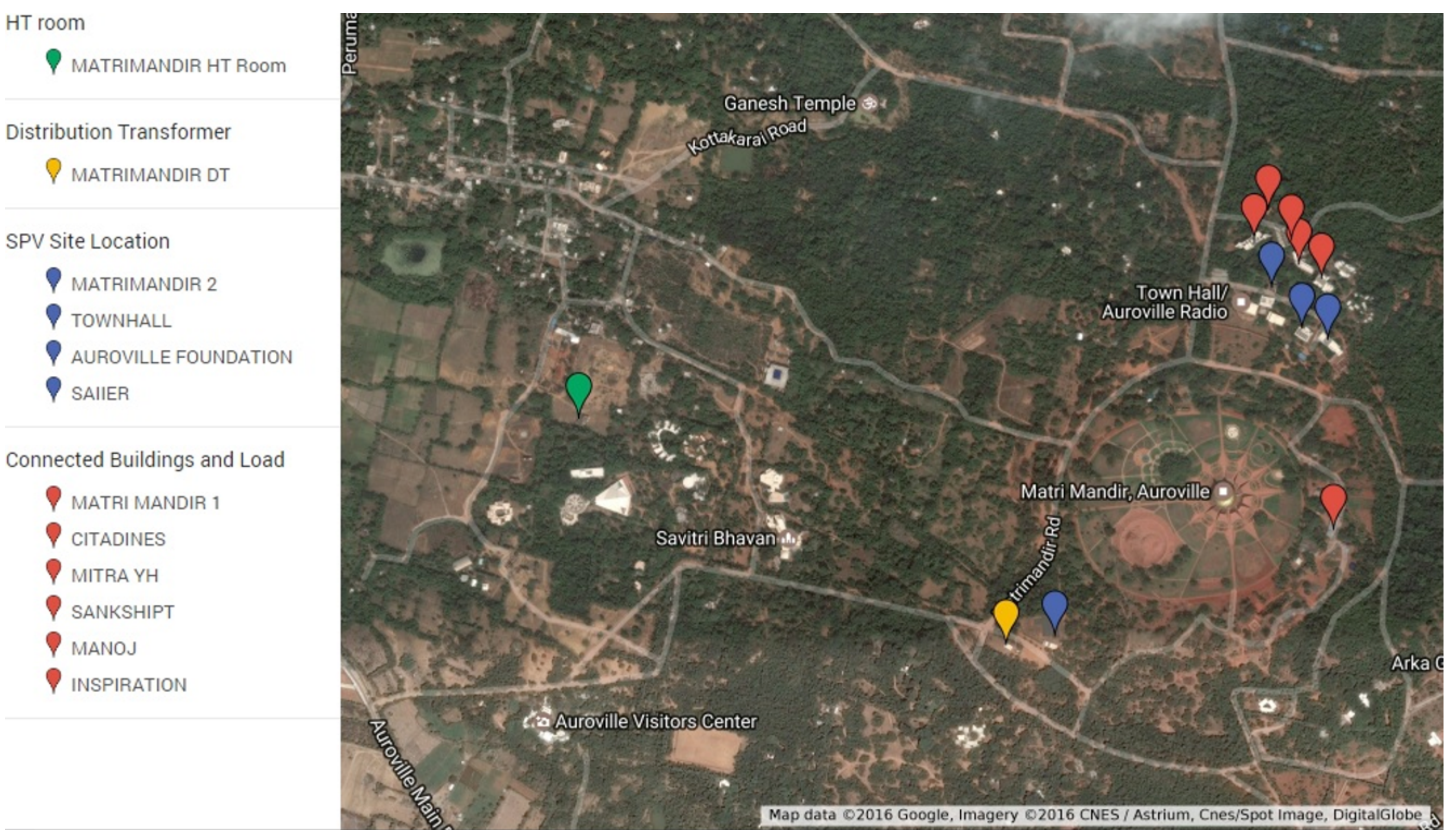


Figure 1 - Matrimandir map

DATA COLLECTION STAGE 1 – PASSIVE OBSERVATION AND DATA LOGGING

The first stage of data collection involved passive observation of the distribution network and continuous data collection to understand the characteristics of the system without interference. Data was logged using digital bidirectional energy meters with data storage capability for a period of 4 months. This data was then used to compare voltage and bidirectional energy flow during the day (sunrise to sunset) and night (sunset to sun rise). Results are shown in the graphs below:

Figure 3 shows that average voltages at the DT are lower during day time than at night time. This could be explained by lower loads, and therefore lower voltage drops at night and cannot be only attributed to grid-connected SPV.

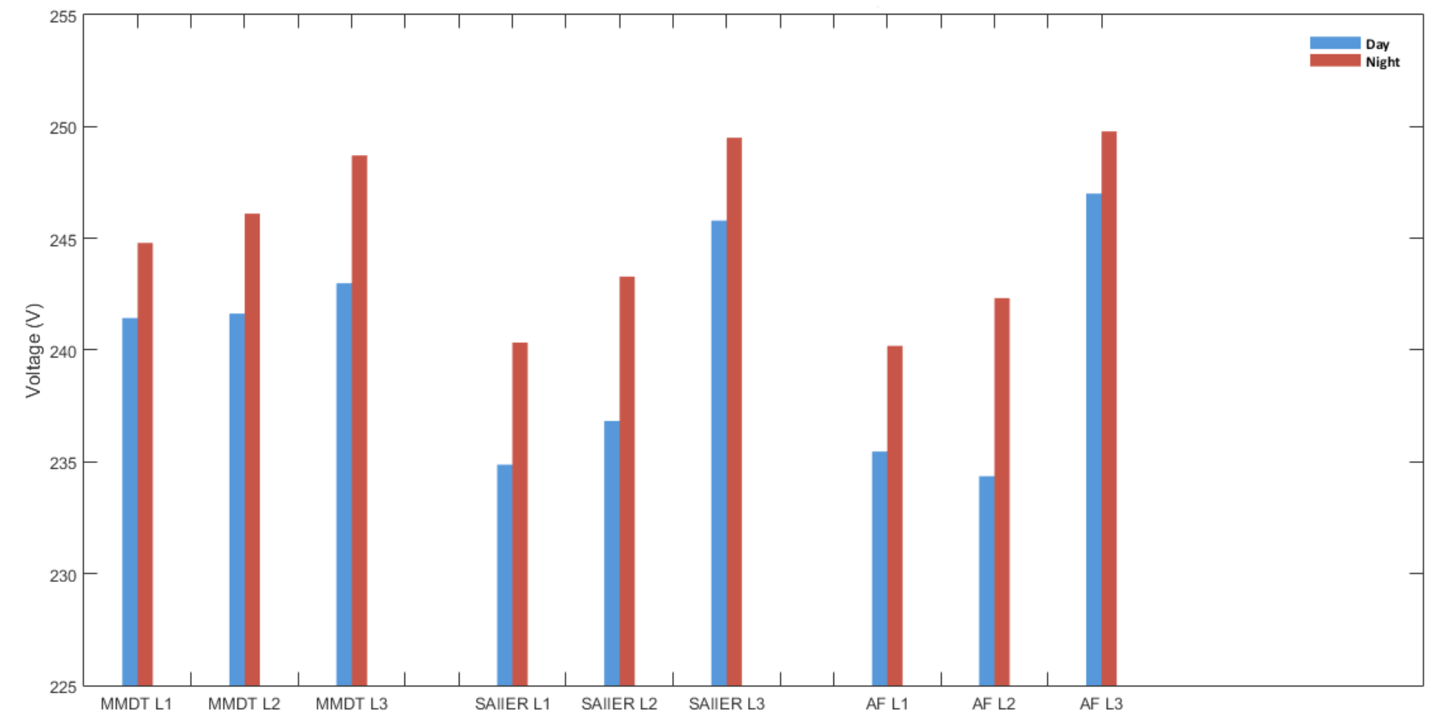
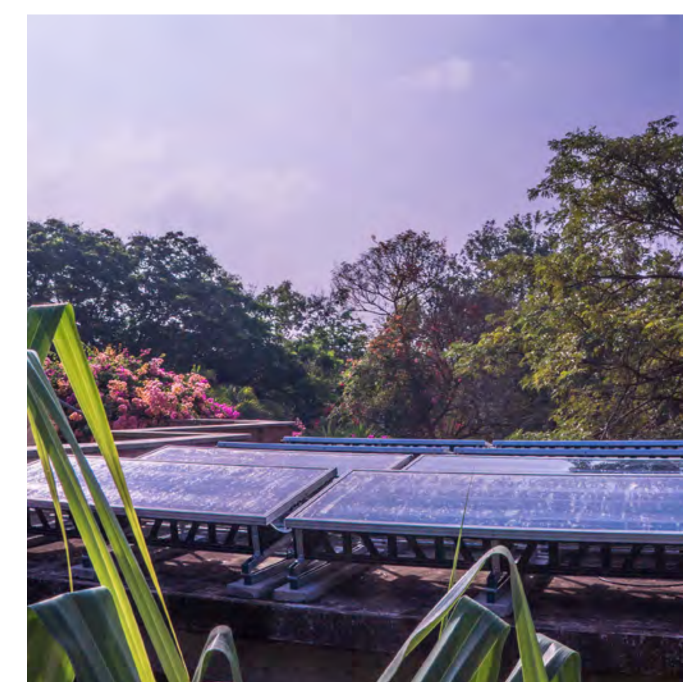


Figure 3 - Matrimandir - Average voltages - Day vs Night



Picture 3 and 4: New Pour Tous SPV Plant (Auroville, India)

Figure 4 shows the daily average voltage profile of the Matrimandir distribution transformer (MMDT) measured at the LT switchboard immediately after the LT terminals of the transformer. The Matrimandir LT distribution network includes the electrical loads of Matrimandir, residences, offices and one workshop (at Matrimandir). The graph depicts the range of daily average voltage which is 230V ± 8%.

Figure 5, shows the daily average load profile of the MMDT. Two spikes are seen, one starting at 8AM attributed to the early morning residential lighting, water heaters and drinking water pumping and the start of work at the Matrimandir. The load then reduces to a low around the lunch break. After the break, the load steadily increases (the second spike) till the end of office hours (around 5PM) following which it tapers down again. If we observe the solar irradiation curve, we see that SPV generation is highest at noon and tapers down on either side.

DATA COLLECTION STAGE 2 – SPV ON/OFF

In this stage, all SPV installations in the Matrimandir distribution network were switched OFF from 11am to 1pm on Tuesdays and Thursdays (regular working days only) in the study period. This eliminated all effects of grid connected SPV on the distribution network. Data was logged by the bi-directional meters during this time; at 1pm all SPV installations were switched ON to return the systems to normal working conditions. The data logged during this 2 hour interval on Tuesdays and Thursdays was compared with data recorded on Mondays, Wednesdays and Fridays during the same 2 hour interval between 11 AM and 1 PM when all SPV was in the ON position. Refer to annex 6A for the detailed ON/OFF schedule.

The key point to be noted is if all SPV installations are switched ON during normal operation hours, the maximum SPV grid penetration is 20% at the Matrimandir distribution network. When the systems are all switched OFF, then the SPV grid penetration falls to 0%. Logging data in both cases, allows us to compare the effect of grid connected SPV. Results are shown below:

Figure 6 shows the comparison between monthly average voltage values for SPV ON and SPV OFF in the Matrimandir distribution transformer and the connected SPV sites for three-phase electricity supply. Average voltage is seen to be lower in all 3 phases when SPV is OFF at both the distribution transformer and the SPV sites. At the LT side of the distribution transformer (marked MM DT), the highest average increase (1.12%) was in Line 3, while Lines 1 and 2 saw an average increase of 1.04% and 0.86% respectively (when SPV was switched ON).

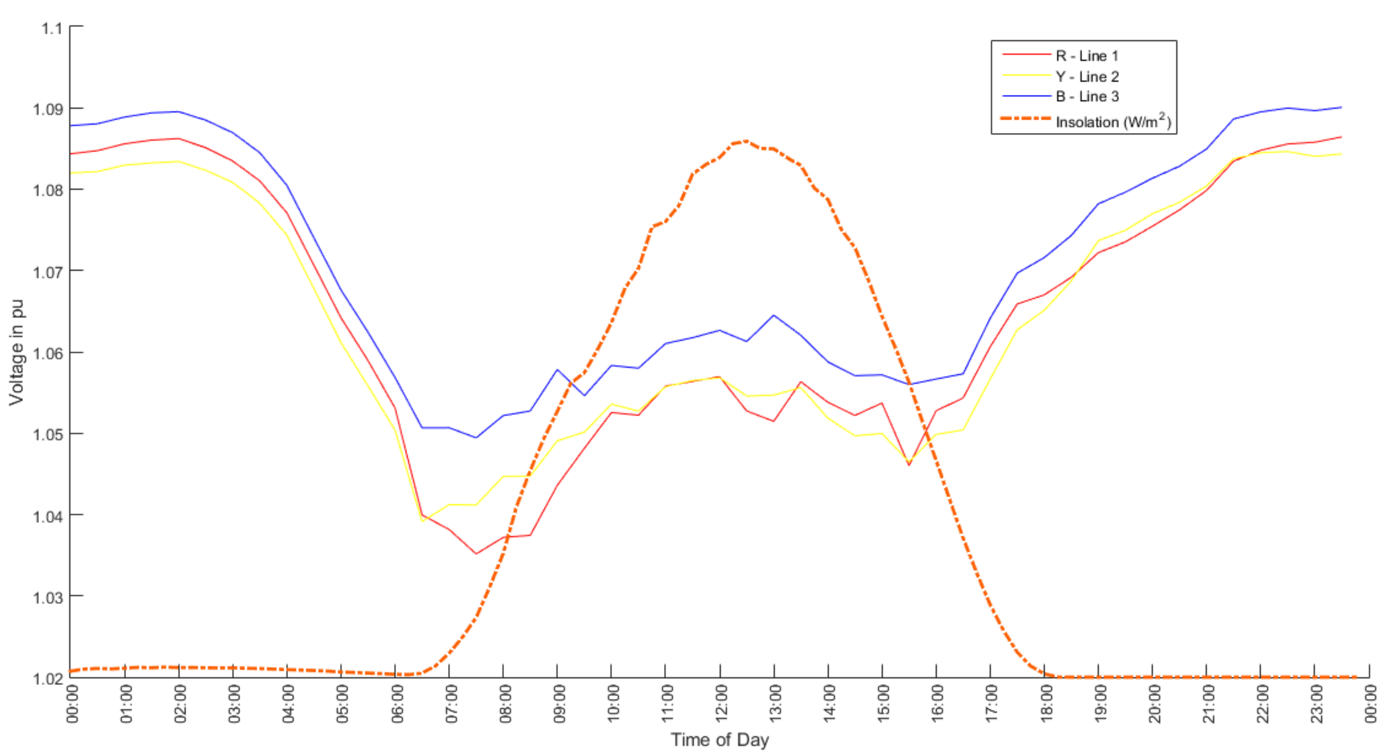


Figure 4 - Daily average voltage profile (with irradiation)

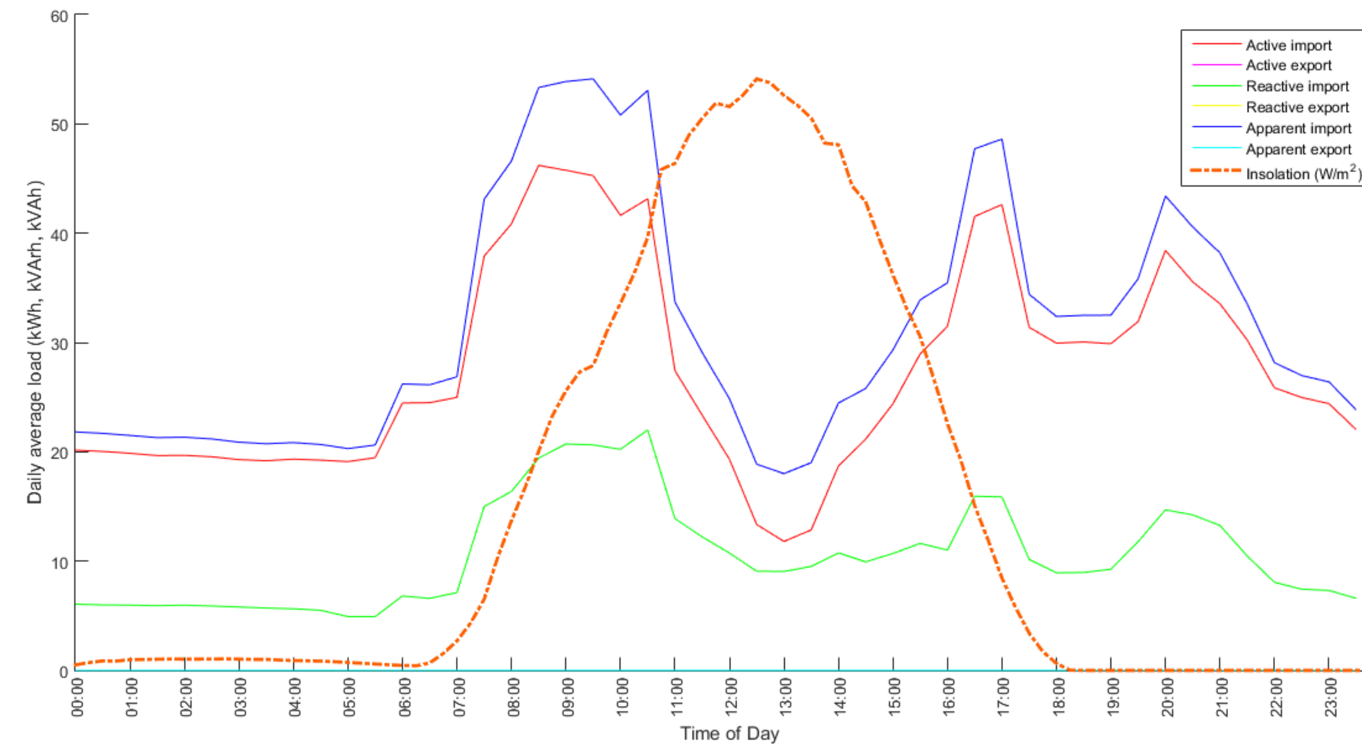


Figure 5 - Daily average load profile (with irradiation)

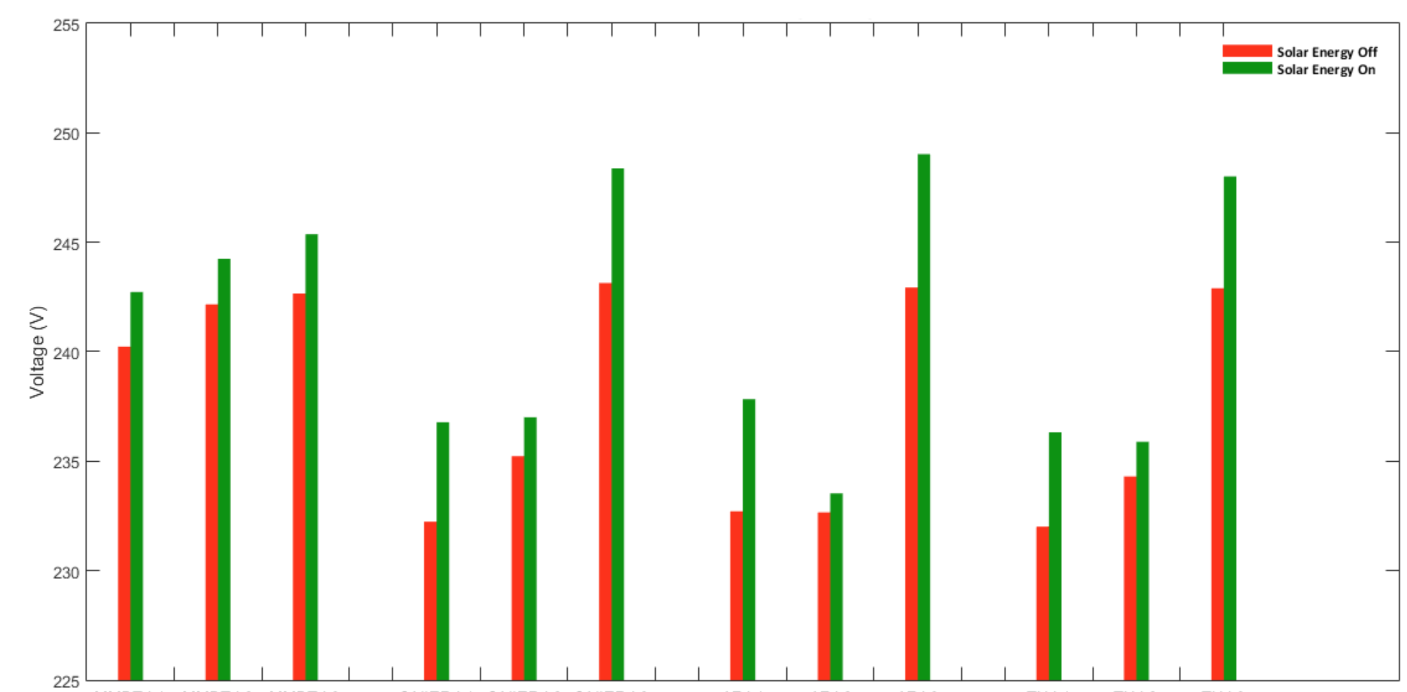


Figure 6 - Matrimandir - Average voltages - SPV On vs Off

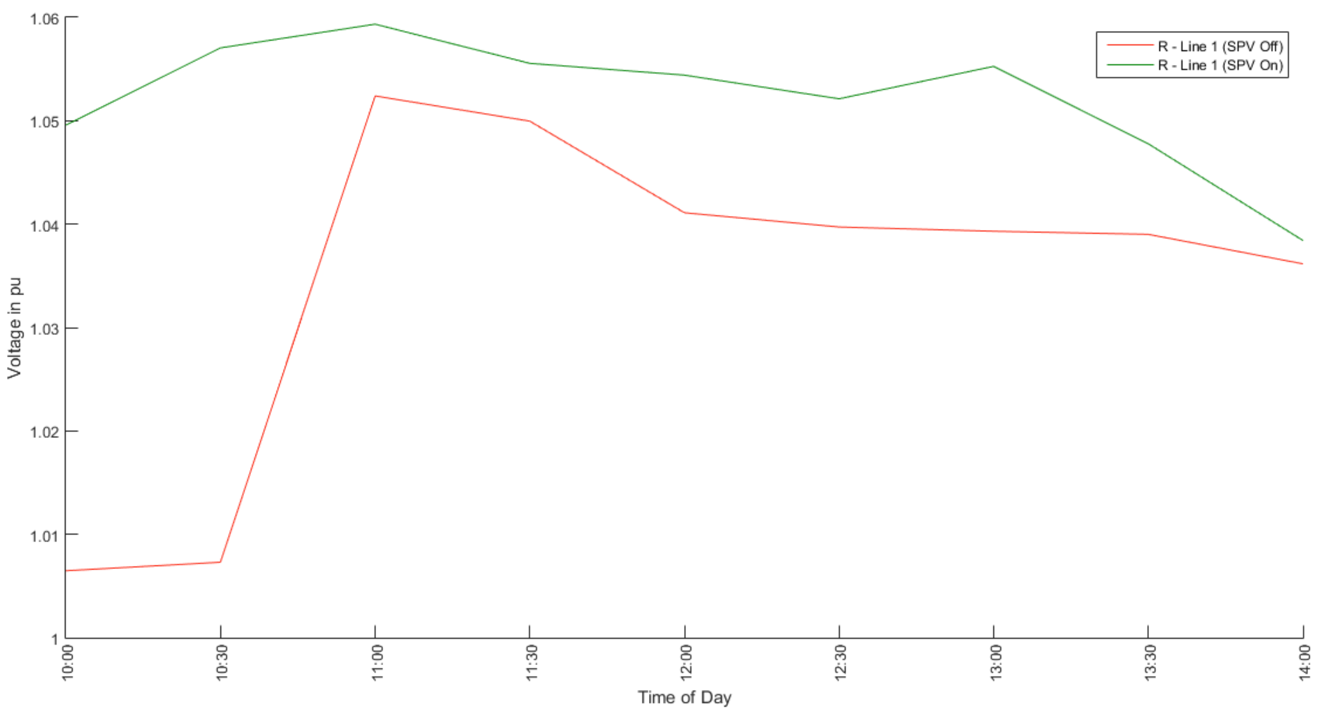


Figure 7 - Matrimandir DT - Voltage On vs Off - Line 1

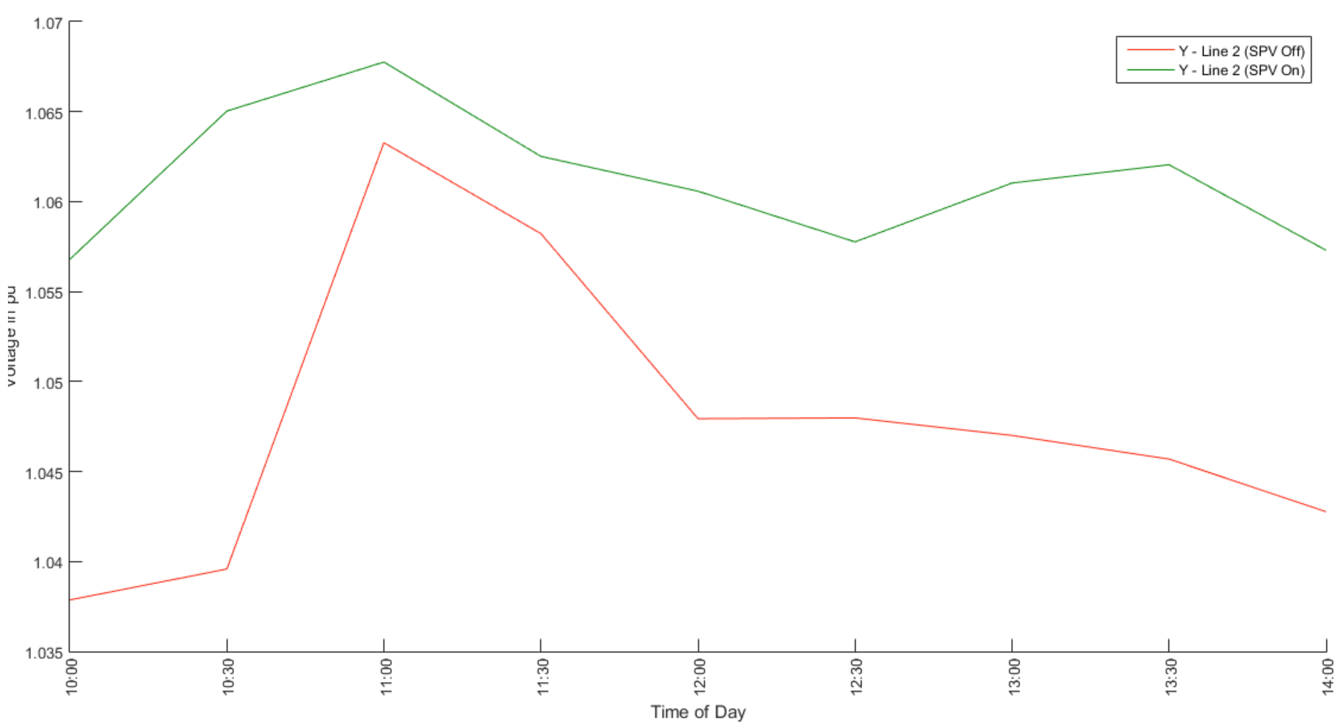


Figure 8 - Matrimandir DT - Voltage On vs Off - Line 2

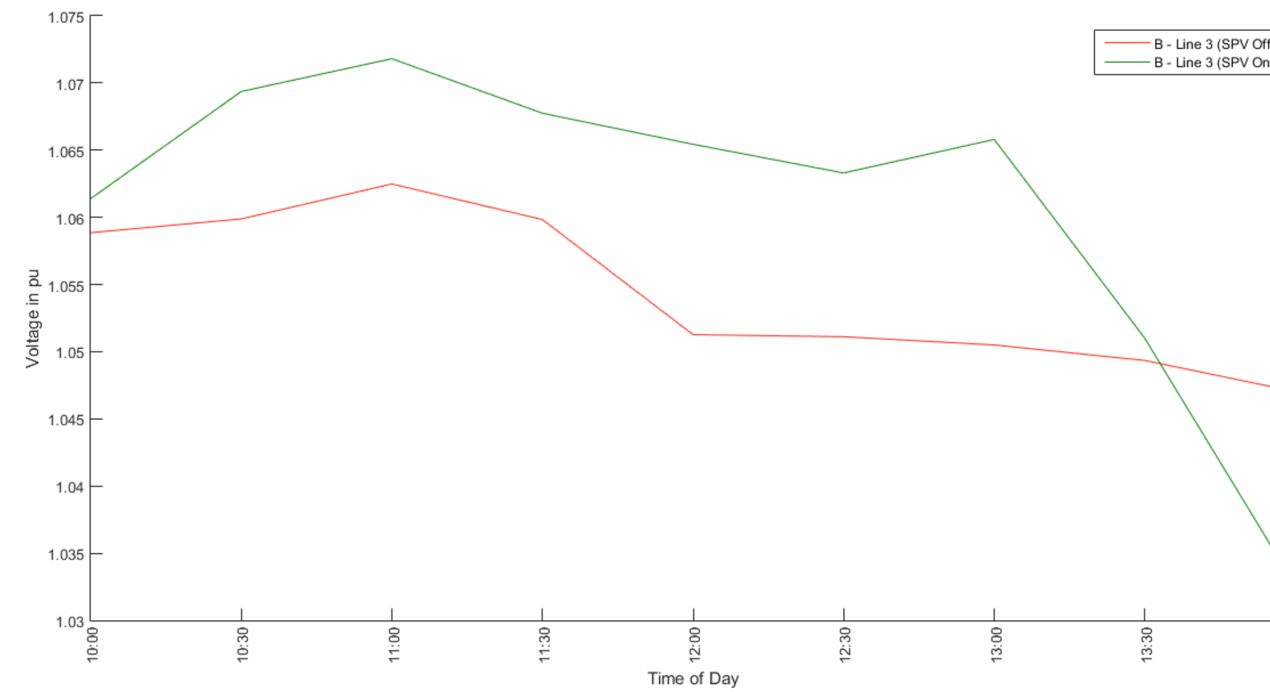


Figure 9 - Matrimandir DT - Voltage On vs Off - Line 3

Figures 7, 8 and 9 show the daily average voltage profile for Lines 1, 2 and 3 respectively at the Matrimandir Distribution Transformer for SPV ON and OFF cases. We can see that voltage is consistently higher for all 3 phases when SPV is ON. Figure 10 shows the difference between daily average active power flow at the Distribution Transformer for SPV ON and OFF. We see that when SPV is ON, lesser active power flow is drawn from the Distribution Transformer which is essentially a lowering of the demand on the transformer.

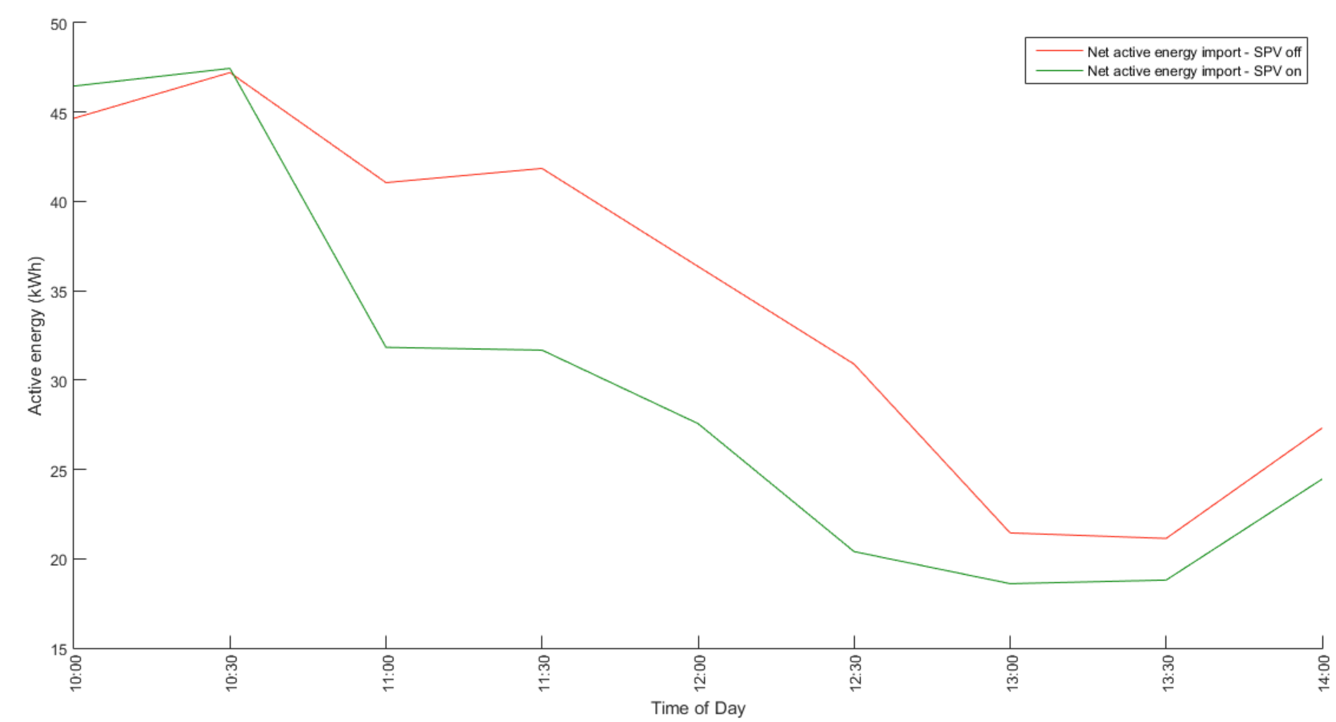


Figure 10 - MM DT - Load On vs Off - Active energy import

Figure 11 shows the bidirectional energy flow data at the low tension side of the distribution transformer. It is seen that at 20% grid penetration, only 1.6 kWh of energy flowed back from the LT to the HT side in the 16-week test period. Ratio of active energy export to import is 1.36x10-5, thus demonstrating that any export due to distributed generation at 20% grid penetration level is negligible.

FINDINGS AT MATRIMANDIR DISTRIBUTION NETWORK

The key findings from the study are given below:

1. The measurements confirm that, as expected, the import of active energy from the grid reduced in proportion to the SPV generation.

2. The tests carried out show that line voltages across the low-tension terminals of the distribution transformer increases utmost by 1.12% (monthly average) when SPV is ON. The phase to neutral voltage at the LT terminals of the transformer remained within a range of 230V ± 8%.

3. During the 4-month passive observation period, 1.6 kWh of active energy export occurred at the LT side of the transformer. During the measurement period 1,17,619.4 kWh of active energy was imported. Therefore the export to import ratio is 0.00001%. This exported energy is negligible compared to energy consumed at the site over the same time period.

4. During the 4-month passive observation period, there was no export of reactive energy to the HT side of the transformer.

Week	Active I	Active E	Reactive I Active I	Reactive I Active E	Reactive E Active E	Reactive E Active I
03/11/15 - 09/11/15	5449.9	0	2923.3	0	0	0
10/11/15 - 16/11/15	6714.2	0	3590.6	0	0	0
17/11/15 - 23/11/15	7687.4	0	4005.3	0	0	0
24/11/15 - 30/11/15	7846.9	0	3903.6	0	0	0
01/12/15 - 07/12/15	8286.9	0	3826.7	0	0	0
08/12/15 - 14/12/15	8333.7	0	4248.1	0	0	0
15/12/15 - 21/12/15	7828.9	0	3582.0	0.1	0	0
22/12/15 - 28/12/15	7767.5	0	3584.6	0.5	0	0
29/11/15 - 04/01/15	6916.6	0	3234.3	0	0	0
05/01/16 - 11/01/16	7686.2	0.7	4407.0	3.8	0	0
12/01/16 - 18/01/16	7625.7	0.1	4403.1	1.9	0	0
19/01/16 - 25/01/16	8704.8	0.4	4690.9	3	0	0
26/01/16 - 01/02/16	7482.1	0	3977.7	0	0	0
02/02/16 - 08/02/16	7862.4	0	4363.9	0.1	0	0
09/02/16 - 15/02/16	8182.7	0.4	4451.4	3.3	0	0
16/02/16 - 19/02/16	3243.5	0	1781.8	0	0	0
Total	**117619.4**	**1.6**	**60974.3**	**12.7**	**0**	**0**

Figure 11: Weekly Average Bidirectional energy flow at the Matrimandir Distribution Transformer

Picture 5: Auroville Consulting SPV Plant (Auroville, India)

Picture 6: New Pour Tous SPV Plant (Auroville, India)

Maroma Distribution Transformer

2. MAROMA DISTRIBUTION TRANSFORMER

The Maroma distribution transformer is a dedicated transformer supplying power to Maroma's industrial unit. The Maroma LT network, has 15 kWp of grid connected SPV distributed over 3 separate 5kWp installations (each with its own inverter) and a 100 kVA 3-phase transformer (22KV / 433V) with an On Load Tap Changer (OLTC).

Unlike the setup at the Matrimandir LT distribution network, the incoming 22 KV HT cable and the 100 kVA 22KV / 433V transformer are part of TNEB infrastructure. The LT distribution system within Maroma's premises including the SPV systems are Auroville-owned. There is an interconnection with TNEB grid at a voltage level of 22KV through an HT service connection. The Maroma (LT) network, similar to the Matrimandir LT distribution network, can be considered to function as a micro (or mini) grid with connectivity to the public grid.

Since the bi-directional energy meter on-site is part of TNEB infrastructure and could not be modified for the purpose of the study, a panel meter with an external data logger was installed.

When all SPV installations are switched on, the network has a peak SPV capacity of 15 kWp which results in a maximum grid penetration ratio of 15% of the distribution transformer capacity.

Table 2 and Figures 12 and 13 provide detailed information of the layout of the LT distribution network at Maroma. The main electrical load is the industrial unit at Maroma, which manufactures fragrances and body-care products. Loads comprise of lights, fans, air conditioning, water pumps and workshop related equipment.

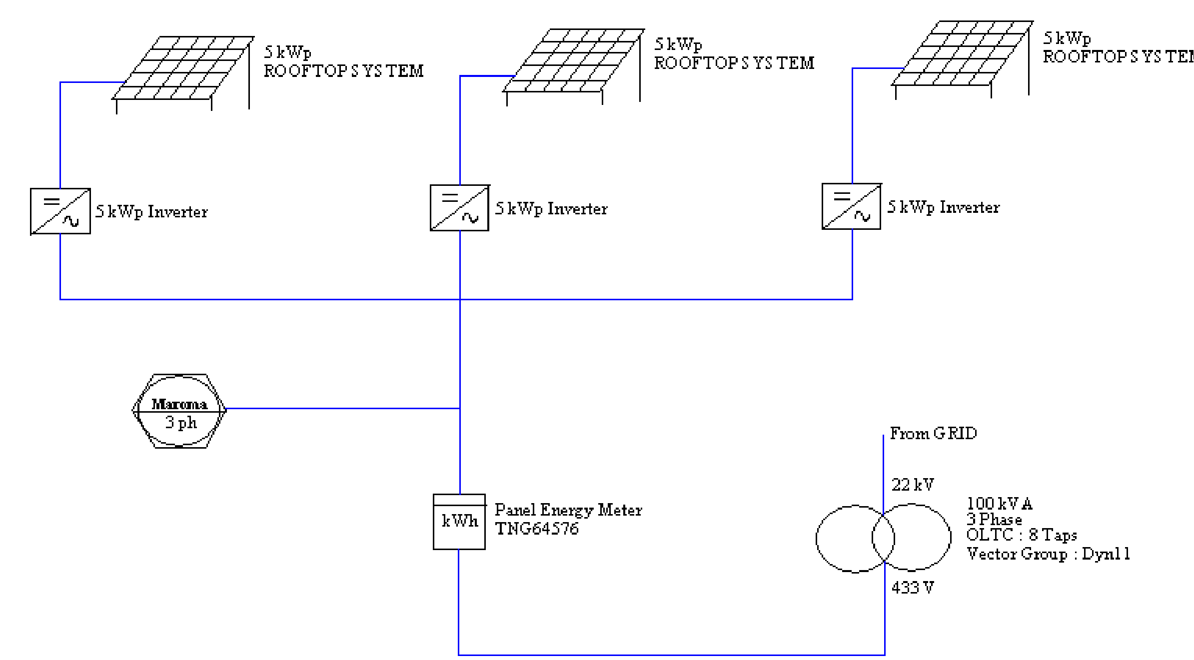


Figure 13: Maroma LT Distribution Network Node Diagram

Building / Cluster name	Connected load (kVA)	Solar PV Capacity (kW)
Maroma	80	15

Table 2: Loads and installed grid connected SPV in Maroma

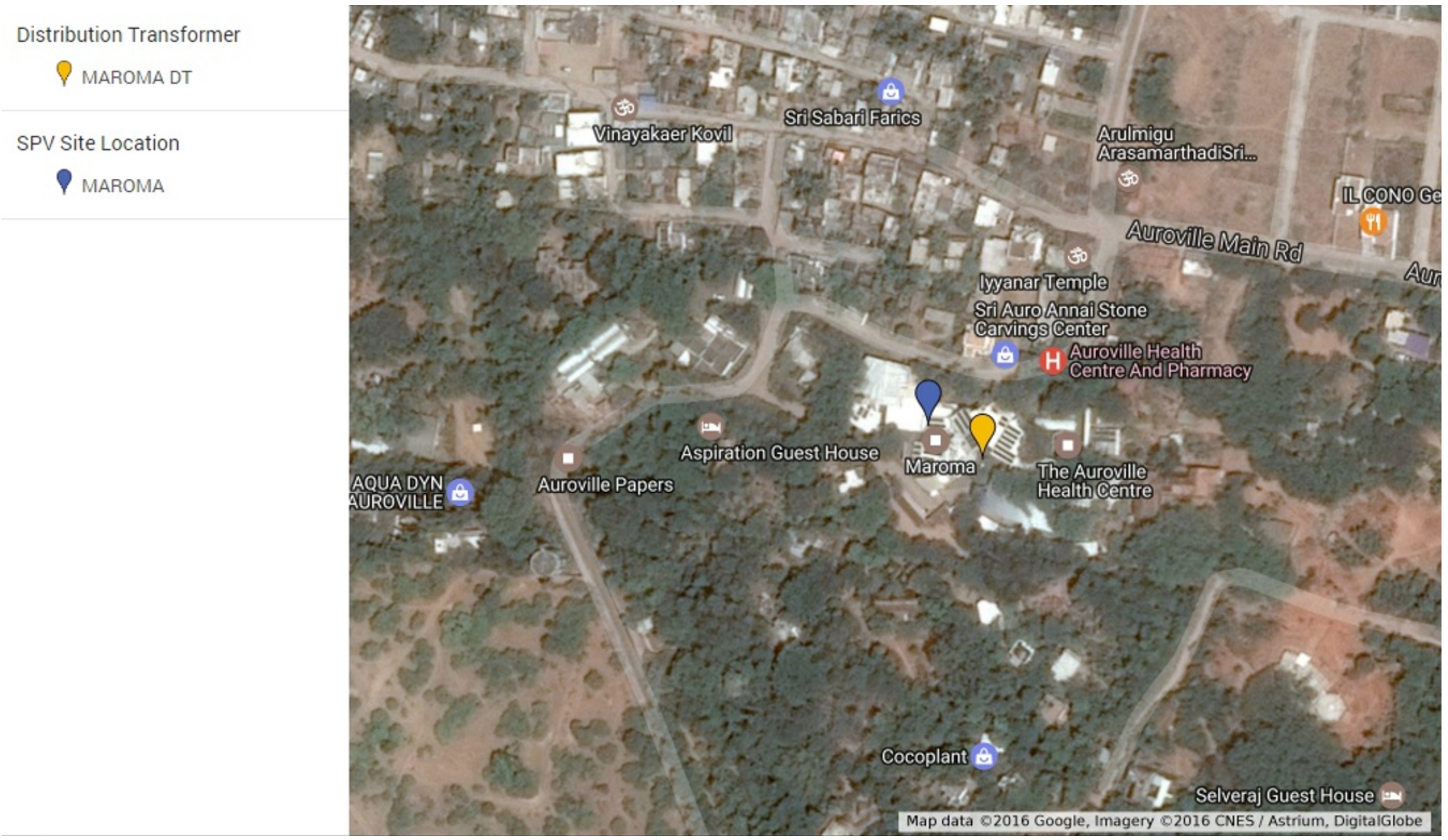


Figure 12 - Maroma map

DATA COLLECTION STAGE 1 – PASSIVE OBSERVATION AND DATA LOGGING

Data was logged using the installed panel meter and data logger for a period of 2 months. During this time period, data was collected passively, with no intervention in the site. This data was then used to compare voltage and load characteristics the day and night.

Figure 14 shows that the average voltages at Maroma DT are lower during day time than at night time. This result is consistent across the 2 distribution networks under study. There could be numerous factors contributing to this occurrence such as changes in loads at night time, changes in incoming voltage supplied by TNEB and no/near-zero solar energy being produced at night. Ascertaining the exact cause(s) of this voltage increase at night compared to the day time is beyond the scope of this study.

Figure 15 shows the daily average voltage profile at the LT terminals of the transformer. This is measured at the LT switchboard immediately after the LT terminals of the transformer. At Maroma, similar to the findings at Matrimandir, the solar irradiation curve and consequent generation by SPV systems is highest at Noon, complementing the load requirements on-site. The daily average voltage graph also clearly shows that the range of daily average voltage is within 230V ± 9%.

Figure 16, which shows the daily average load profile of Maroma, has 2 plateaus of high demand periods. The plateau between 8AM and 12 Noon can be directly attributed to production hours at the industrial unit. There is a dip in demand during lunch followed by a second high load period corresponding to the rest of the work day.

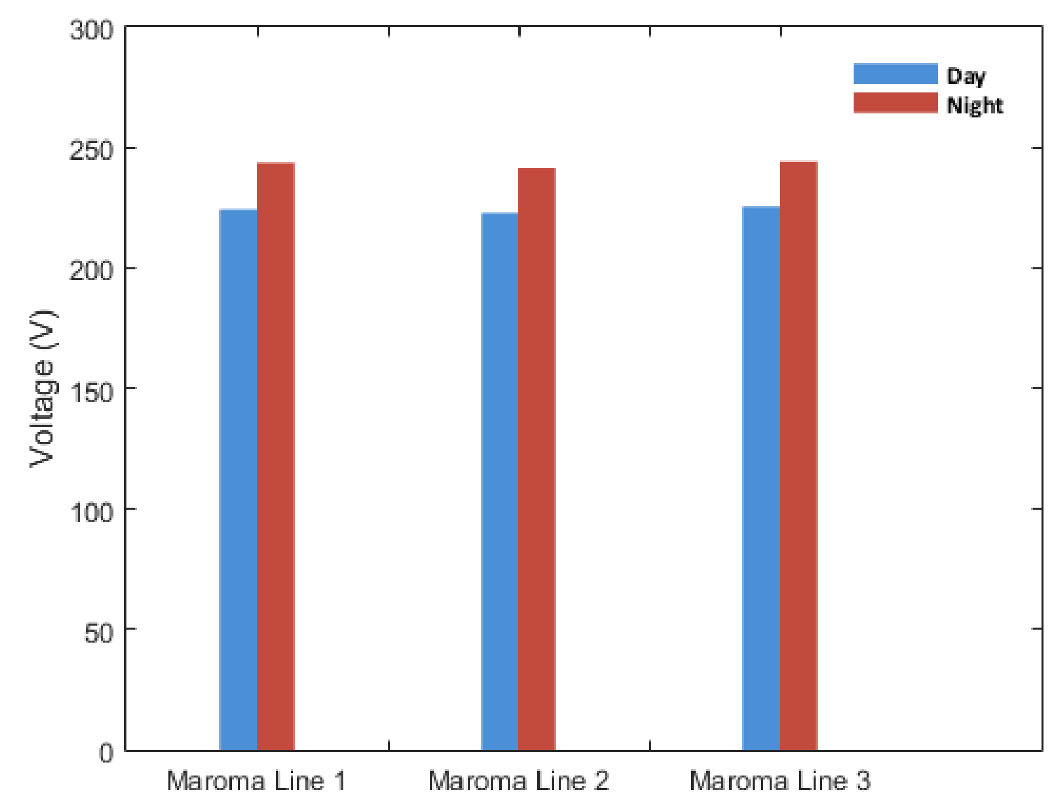


Figure 14: Maroma - Comparison of Monthly Average Voltages for Day and Night Scenarios

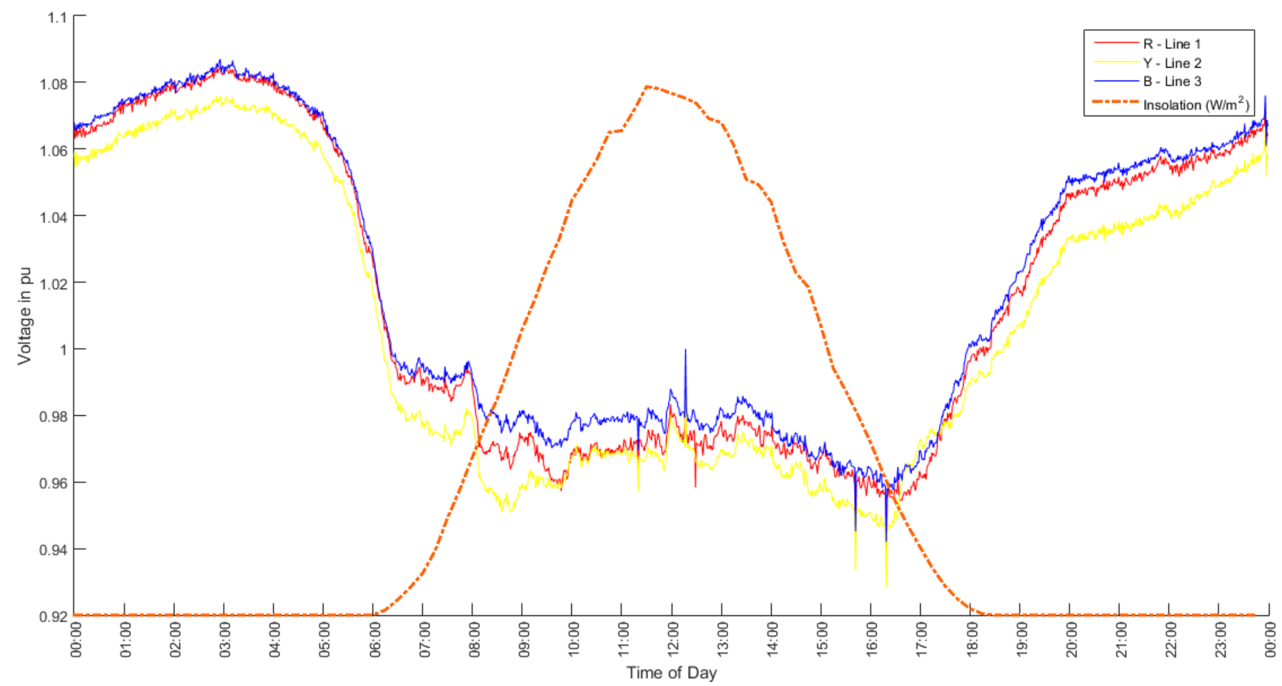


Figure 15: Maroma Daily Average Voltage Profile Superimposed over Solar Irradiation Curve

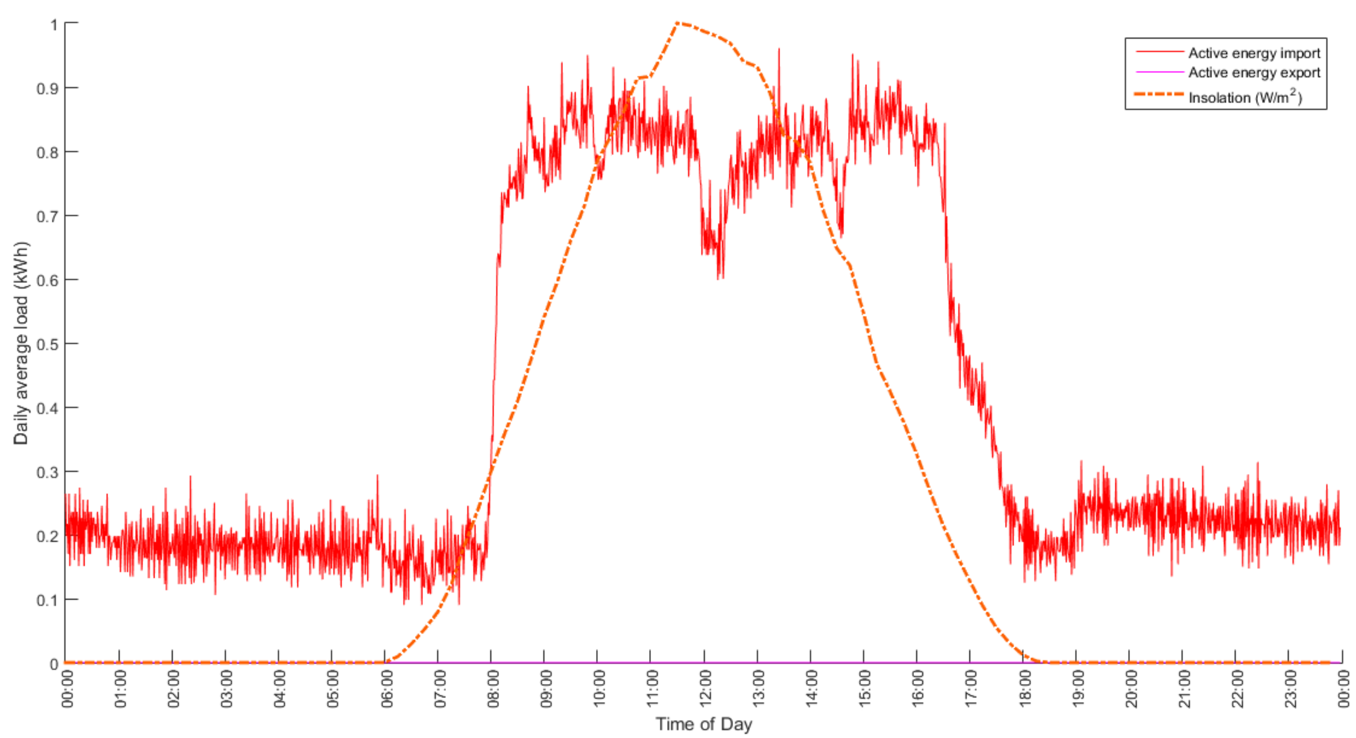


Figure 16: Maroma Daily Average Load Profile Superimposed over Solar Irradiation Curve

DATA COLLECTION STAGE 2 – SPV ON/OFF

For this stage of data collection, the experimental procedure is the same as the one carried out by Matrimandir LT distribution grid. When all SPV installations are switched ON during normal operation hours, the maximum SPV grid penetration is 15%. When all SPV is switched off, SPV grid penetration is 0%.

All SPV installations in Maroma were switched off at 11AM and 1PM on Tuesdays and Thursdays (non-public holidays) in the study period, thereby eliminating all effects of grid connected SPV on the distribution network. The panel meter and data logger continued to collect data during this period. All SPV installations were turned back on at 1PM to return the system to normal operating conditions. The data logged during this 2 hour interval (11 AM to 1 PM) on Tuesdays and Thursdays was compared with data recorded on Mondays, Wednesdays and Fridays when SPV was left on. Annex 6B provides the SPV On/Off schedule.

Figure 17 shows the comparison between monthly average voltage values for SPV ON and SPV OFF cases in the distribution transformer and the SPV sites for Phases 1, 2 and 3 in the 3-phase supply to Maroma. There is a negligible increase in line voltages when SPV is on of 0.26% in Line 2, 0.24% in Line 3 and a mere a 0.02% in Line 1.

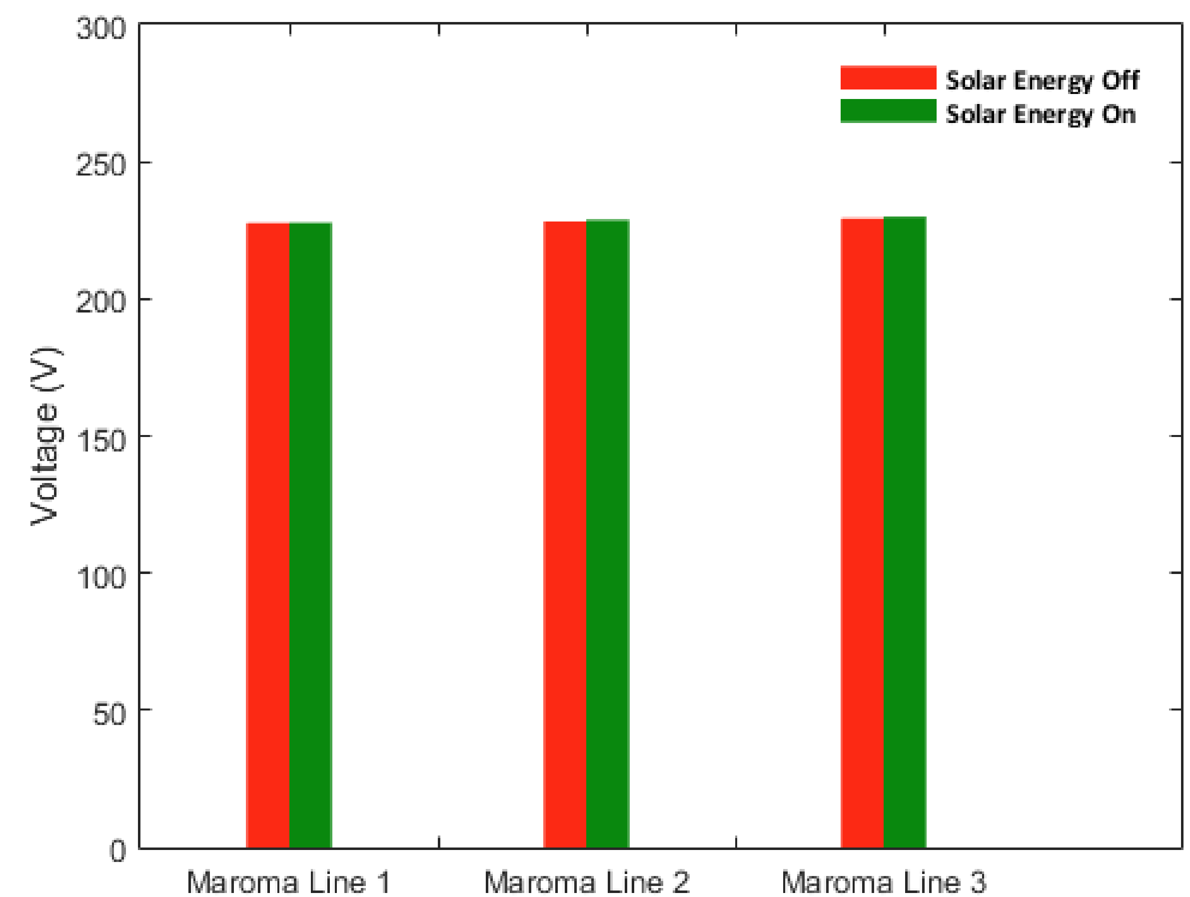


Figure 17: Maroma Monthly Average Voltage – Solar Energy On vs. Off

Figure 18: Daily Average Voltage Profile at Maroma for SPV On and Off – Line 1

Figure 19: Daily Average Voltage Profile at Maroma for SPV On and Off – Line 2

Figure 20: Daily Average Voltage Profile at Maroma for SPV On and Off – Line 3

Figure 21 shows the difference between daily average active power flow at the LT terminals of the Maroma DT for SPV ON and OFF cases. When SPV is ON, lesser active power flow is drawn from the Distribution Transformer which is essentially a lowering of the demand on the transformer. This result is consistent across both the distribution network sites (Matrimandir and Maroma) under study.

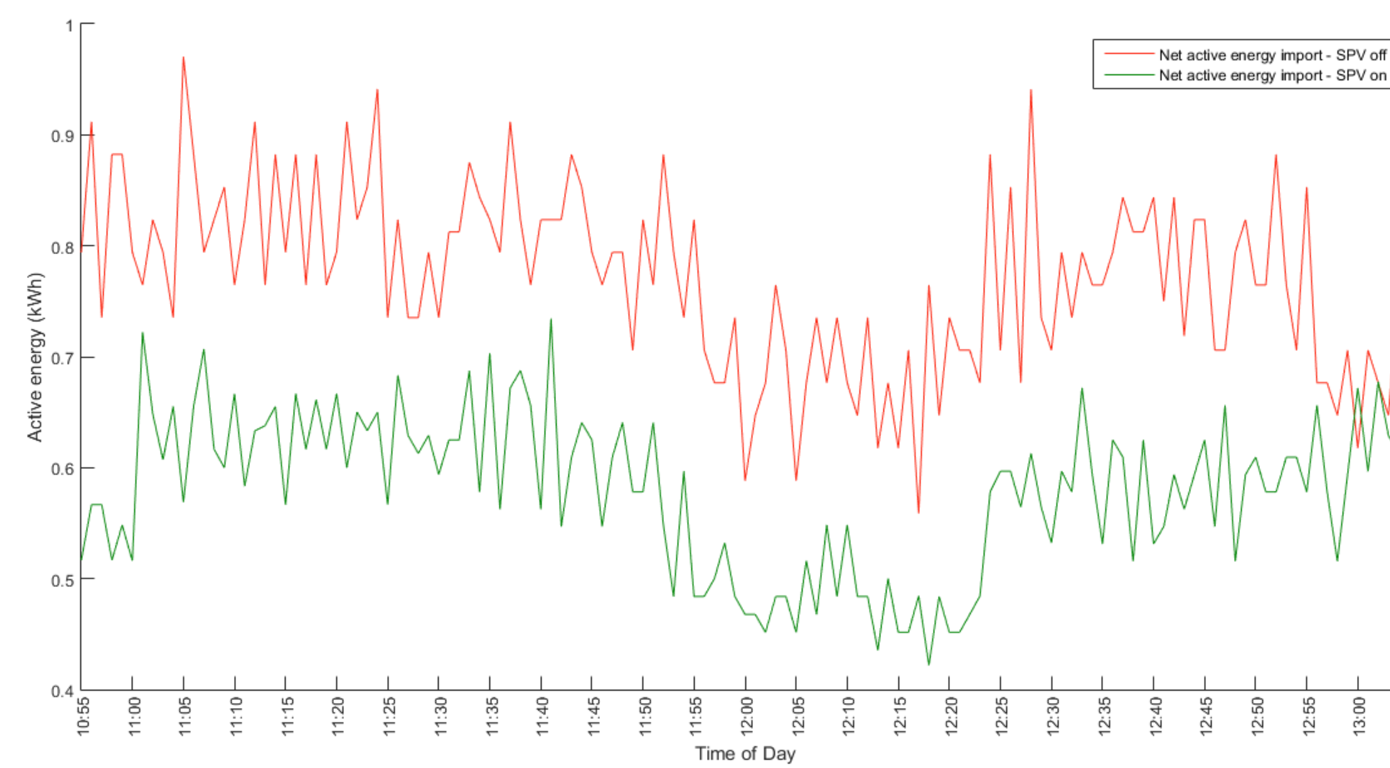


Figure 21: Daily Average Bi-directional Active Power Profile at Maroma DT for SPV On and Off

Week	Active I	Active E
01/10/16 - 07/10/16	5449.9	0.0
08/10/16 - 14/10/16	6714.2	0.0
15/10/16 - 21/10/16	7687.4	0.0
22/10/16 - 28/10/16	7846.9	0.0
29/10/16 - 04/11/16	8286.9	0.0
05/11/16 - 11/11/16	8333.7	0.0
12/11/16 - 18/11/16	7828.9	0.0
19/11/16 - 25/11/16	7767.5	0.0
26/11/16 - 30/12/16	6916.6	0.0
Total	**117619.4**	**0.0**

Figure 22: Weekly Average Bidirectional Energy Flow at the Maroma Distribution Transformer

Figure 22 shows the bi-directional energy flow data at the low tension side of the distribution transformer. It is seen that at 15% grid penetration, no energy flowed back from the LT to the HT side during the test period (ratio of active energy export to import goes to 0), thus demonstrating that no energy export occurred at 15% grid penetration. This straightaway removes from the table any discussion of issues caused by backflow of energy to the HT side of the DT.

FINDINGS AT MAROMA:

The key findings from the study are given below:

1. The measurements confirm that the import of active energy from the grid reduced in proportion to the SPV generation.

2. The tests carried out show that voltage across the low-tension terminals of the distribution transformer increases by a maximum of 0.26% when SPV is ON. The phase to neutral voltage at the LT terminals of the transformer remained within a range of 230V ± 9%.

3. During the 2-month passive observation period, there was no instance of any active energy export to the LT side of the transformer. During the measurement period 31,085.5 kWh of active energy was imported. This makes the export to import ratio is 0% (irrespective of import value since export is 0).

4. During the 2-month passive observation period, there was no export of reactive energy to the HT side of the transformer.

Picture 8: Matrimandir SPV Plant (Auroville, India)

Picture 9: Pondicherry Ashram SPV Plant (Puduchery, India)

Overarching Results

OVERARCHING RESULTS:

The 2 sites that were studied – Maroma and Matrimandir LT distribution networks, are distinctly different in a number of ways. The Matrimandir distribution network experiences a mixed load and supplies power to Matrimandir and the buildings in the administrative area of Auroville. Maroma, on the other hand, experiences a concentrated industrial load with just one feeder running to the factory unit. In spite of differences in type, spread and nature of demand on the distribution transformers at the respective sites, when it comes to effect of grid connected SPV, there are some striking similarities -

1. Consistent across both the sites studied, presence of active SPV installations leads to a corresponding decrease in active energy import as expected.

A. SPV generation helps reduce the load on the grid. This leads to lesser instantaneous load (instantaneous active power import) which in turn means a reduced capacity demand from grid components including the Distribution Transformer (DT).
B. SPV generation helps reduce the amount of active energy imported from the grid, which reduces the amount of energy that has to be supplied to the end-user by the distribution transformer.

2. In both sites, Matrimandir LT distribution grid and Maroma, line voltages were marginally higher when SPV was on but this increase is negligible (≤ 1.12%).

A. It should be noted that the change in voltage cannot be entirely attributed to the solar PV grid penetration.

3. Active energy export at SPV grid penetration ratio of ≤ 20% is either non-existent or negligible for these 2 sites. This directly means that all energy generated through SPV was absorbed by loads on the LT side of the distribution transformer or dissipated during transmission within the LT distribution network.

4. There was no export of reactive energy to the HT side of the distribution transformer at SPV grid penetration levels of ≤ 20%.

5. In addition, the study also found that the amount by which voltage fluctuates when SPV is ON, is lower than the voltage fluctuations when SPV is OFF, as shown in the table and graph below.

Distribution transformer (LT Terminals)			Daily Average Voltages (V)		
			Max	Min	Difference
Matrimandir	**SPV Off**	**Line 1**	242.0518	231.4900	**10.5618**
		Line 2	244.5529	238.7082	**5.8447**
		Line 3	244.3718	240.8165	**3.5553**
	SPV On	**Line 1**	243.6476	238.8360	**4.8116**
		Line 2	245.5844	243.0619	**2.5225**
		Line 3	246.5164	237.4900	**9.0264**
Maroma	**SPV Off**	**Line 1**	232.4791	224.0839	**8.3952**
		Line 2	233.6117	224.8349	**8.7769**
		Line 3	234.7691	226.2626	**8.5066**
	SPV On	**Line 1**	231.6757	223.5914	**8.0843**
		Line 2	231.7749	224.1098	**7.6651**
		Line 3	233.4345	225.5253	**7.9091**

Table 3: Voltage bandwidth values for SPV On and Off cases

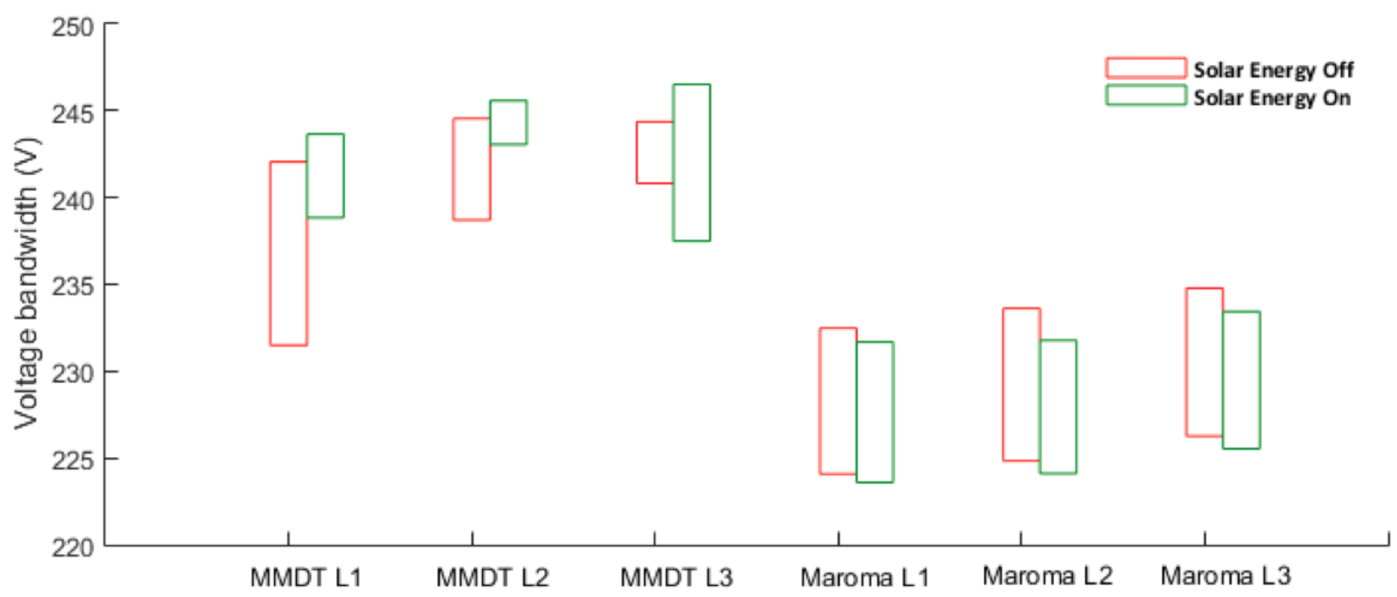


Figure 23: Voltage bandwidth plot for SPV On and Off cases

It could be reasoned that the support SPV provides to the grid in satisfying energy demand from the loads, reduces the magnitude of voltage swings, thus having a stabilizing effect.

That being said, there could be numerous factors contributing to voltage fluctuations such as changes in loads, changes in incoming voltage supplied by TNEB and/or amount of solar energy being produced. Ascertaining the exact cause(s) of various voltage fluctuations is beyond the scope of this study.

CHALLENGES AND SUGGESTIONS:

As with any study of this scale, planning can reduce the chances of encountering roadblocks but not eliminate them entirely. Below are some of the challenges the team faced in undertaking this study along with some suggestions which could be instrumental in steepening the learning curve of subsequent studies.

TECHNICAL:

• Grid connected SPV systems employ an inverter to convert the DC power generated to AC power that is usable by electrical equipment. Inverters produce harmonics in the process of DC-to-AC conversion which adversely affects power quality. The study found the need for frequency domain analysis of bidirectional power flow and voltage since these could be crucial elements that require better representation in a data driven model.

• Similarly, including automation implements such as remote monitoring and control systems could help save precious time and manpower thus allowing for greater flexibility in research methodologies and higher granularity of data.

• Feeder characteristics, which are beyond the scope of this research study, is also an important factor in grid performance and can be reliably used to form metrics for examining grid conditions. Exploring ways to include GIS data and feeder characteristics in the modeling process, by allocating time, funds and additional man-power, could be pivotal steps that help improve accuracy.

• Another important factor that affects SPV generation is weather variability (parameters such as irradiance, ambient and panel temperature, humidity, wind speed, etc). The study utilized data from a pre-installed weather monitoring station at the SPV site within the Matrimandir premises in Auroville. Weather conditions may be different at different points in the distribution network being studied. Irradiance, for instance, is affected by cloud cover and this could vary drastically even between sites that are located near each other. Incorporating weather data into the model would require weather-monitoring stations being set up at more SPV sites. It is for these reasons that as much as practically possible, measurement comparisons, of SPV on and off conditions

for instance, have been done among consecutive days with a reasonable assumption that days chronologically close to each other will on average have roughly the same weather conditions.

• There are also other factors that may have affected measurements, such as load variability at different times in the same day or across the span of a few months, as well as variability in voltage supplied by the grid. These have been beyond the control of the project team.

SOCIAL:

• A study of this nature requires access to solar PV systems of all involved consumers and cooperation from TNEB for installation of meters at their distribution transformers and LT lines. Further studies of this nature would benefit from allocation of more resources (time, funds, man-power, etc.) in the initial stage. This will greatly reduce associated delays during the rest of the study time-line.

• This study required the close coordination of SPV system function across various load buildings within the Matrimandir LT distribution network (for example, turning SPV on/off across the entire site). These operations required that SPV be turned off at a time suitable for the study and while ensuring the functioning of respective buildings. This required the project team to identify a time slot on working days that satisfied 2 conditions –

i) SPV be on/off action be conducted at a time such that the effect of SPV can be clearly distinguished.

ii) And it also required that all involved building stewards agree on a common schedule for SPV on/off operations after evaluating the chances of such actions affecting normal building function.

• Lack of a sense of community and reluctance to share information with a team outside of their own organization was a major reason for lack of progress in attempts to identify, access and evaluate potential sites belonging to private entities outside of Auroville.

•The importance of support from relevant regulatory bodies, with regard to location and identification of new sites, cannot be stressed enough.

FUNDING:

Future studies could include financial resources for –
• Bi-directional meters capable of measuring harmonics for frequency domain analysis in future studies could provide useful insights into the effect of different levels SPV grid penetration on quality of power supply.

• Remote monitoring and control systems to move towards automation which will aid in collecting better data and reduce required man-power.

• Acquiring and incorporating GIS data and tools to get a better picture of field parameters.

• A weather monitoring station for each site to accurately incorporate, analyze and decouple effects of weather parameters from effects of SPV grid penetration.

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Annexes

ANNEX 1: LIST OF PARAMETERS

A – MATRIMANDIR LT DISTRIBUTION NETWORK

Parameter	Integration	Frequency	Description
Voltage	30 min	Monthly	3 – phase Voltages
Current	30 min	Monthly	3 – phase Current
Active power	30 min	Monthly	Active Import and Export
Reactive power	30 min	Monthly	Reactive Four Quadrant
Apparent power	30 min	Monthly	Apparent Import and Export
Power factor	30 min	Monthly	Average Power Factor Import & Export
Weather Data	15 min	Daily	Solar Irradiance
	15 min	Daily	Temperature
	15 min	Daily	Wind Speed
Solar Production	15 min	Daily	SPV Site A – (Near end)
	15 min	Daily	SPV Site B – (Far end)
V, I, R, Q, S, ϕ, f	**1 min**	**Real time**	**Wattmon – LT Feeder Head**

B - MAROMA

Parameter	Integration	Frequency	Description
Voltage	1 min	Real Time	3 – phase Voltages
Current	1 min	Real Time	3 – phase Current
Active power	1 min	Real Time	Active Import and Export
Reactive power	1 min	Real Time	Reactive Import
Apparent power	1 min	-	-
Power factor	1 min	Real Time	3 – phase Power Fact
Weather Data	15 min	Daily	Solar Irradiance
	15 min	Daily	Temperature
	15 min	Daily	Wind Speed
Solar Poduction	1 Day	Daily	Rooftop SPV

ANNEX 2: OBIS CODES OF PARAMETERS

No	Obis			Description	Matrimandir	Maroma
1	0	9	2	Date	Logged	Logged
2	0	9	1	Real Time	Logged	Logged
3	1	8	0	Active Energy Import (+A) total [kWh]	Logged	Logged
4	2	8	0	Active Energy Export (-A) total [kWh]	Logged	Logged
5	5	8	0	Reactive Energy Import (+Ri) (Q1) [KVArh]	Logged	-
6	6	8	0	Reactive Energy Export (+Rc) (Q2) [KVArh]	Logged	-
7	7	8	0	Reactive Energy Import (-Ri) (Q3) [KVArh]	Logged	-
8	8	8	0	Reactive Energy Export (-Rc) (Q4) [KVArh]	Logged	-
9	9	8	0	Apparent Energy Import (+S) total [kVAh]	Logged	-
10	10	8	0	Apparent Energy Export (-S) total [kVAh]	Logged	-
11	16	8	0	Active Energy Net (l+Al - l-Al) [kWh]	Logged	-
12	32	7	0	Instantaneous Voltage (U) In Phase L1 [V]	Logged	Logged
13	52	7	0	Instantaneous Voltage (U) In Phase L2 [V]	Logged	Logged
14	72	7	0	Instantaneous Voltage (U) In Phase L3 [V]	Logged	Logged
15	31	7	0	Instantaneous Current (I) In Phase L1 [A]	Logged	Logged
16	51	7	0	Instantaneous Current (I) In Phase L2 [A]	Logged	Logged
17	71	7	0	Instantaneous Current (I) In Phase L3 [A]	Logged	Logged
18	14	7	0	Frequency [Hz]	Logged	Logged

ANNEX 3: DISTRIBUTION TRANSFORMER SPECIFICATION SHEET

Project No			(for office use)	
Organization Name				
DISCOM				
Department/Division				
Transformer Identification Number				
Location - Village/Taluka/District/State				
Total Sanctioned Load				
Sl No	**Parameter**	**Unit**	**Value**	**Remark**
1	Make and Model			
2	Rated nameplate capacity	KVA		
3	Frequency	Hz		
4	Voltage at No Load – HV	Volt		
5	Voltage at No Load - LV	Volt		
6	Current – HV	Ampere		
7	Current – LV	Ampere		
8	Phase – HV			
9	Phase – LV			
10	Vector Group Reference	e.g. Dyn11		
11	Impedance Volts	%		
	Contact Person		DISCOM Engineer	
Name				
Signature				
Date				

ANNEX 4: DATA CLEAN-UP CODE FLOW

• Step 1: Import data into MATLAB.
• Step 2: Process date time information and identify meter information.
  * Merge the Date with Interval Start from the CSV File.
  * Check the date-time stamps at start and end of file.
  * Record filename start date and end date information in separate table for reference.
• Step 3: Remove all the missing date and time marked as NaT (not-a-time).
• Step 4: Mark and remove all the non-numeric values marked as NaN (not-a-number).
• Step 5: Identify unique data and remove any over lapping data.
• Step 6: Identify 0 values in Voltage or Energy and make power cut log.
• Step 7: Finally clean all the information to present unique non zero values for further analysis and processing.

ANNEX 5: DATA VISUALIZATION CODE FLOW

• Set base voltage as 230V and the hours of the day being plotted (10:30 AM to 1:30 PM in case of On/Off) in the daily average load/voltage profile.
• Load relevant data from mat files keeping only data corresponding to dates on which On/Off activity was conducted.
• Extract voltage and bidirectional power flow parameters separately.
• Calculate average over integration period of all the individually extracted parameters for the given daily experiment interval.
• Calculate and plot daily average p.u. voltage for given time interval of day using declared base voltage.
• Plot daily average load profile for given time interval of day.

ANNEX 6: SPV ON/OFF SCHEDULE

The following tables document the SPV on / off schedule at both LT distribution networks. The time period when the SPV was turned off was 11am to 1pm in all instances.

A – MATRIMANDIR LT DISTRIBUTION NETWORK

Date	Matrimandir	Town Hall	SAIIER	Auroville Foundation
04-Apr-16	Left on	Left on	Left on	Left on
05-Apr-16	Switched off & on	Switched off & on	Switched off & on	Switched off & on
06-Apr-16	Left on	Left on	Left on	Left on
07-Apr-16	Switched off & on	Switched off & on	Switched off & on	Switched off & on
08-Apr-16	Left on	Left on	Left on	Left on
09-Apr-16	Weekend excluded	Weekend excluded	Weekend excluded	Weekend excluded
10-Apr-16	Weekend excluded	Weekend excluded	Weekend excluded	Weekend excluded
11-Apr-16	Left on	Left on	Left on	Left on
12-Apr-16	Switched off & on	Switched off & on	Switched off & on	Switched off & on
13-Apr-16	Left on	Left on	Left on	Left on
14-Apr-16	- Rescheduled -	- Rescheduled -	- Rescheduled -	- Rescheduled -
15-Apr-16	Switched off & on	Switched off & on	Switched off & on	Switched off & on
16-Apr-16	Weekend excluded	Weekend excluded	Weekend excluded	Weekend excluded
17-Apr-16	Weekend excluded	Weekend excluded	Weekend excluded	Weekend excluded
18-Apr-16	Left on	Left on	Left on	Left on
19-Apr-16	Switched off & on	Switched off & on	Switched off & on	Switched off & on
20-Apr-16	Left on	Left on	Left on	Left on
21-Apr-16	Switched off & on	Switched off & on	Switched off & on	Switched off & on
22-Apr-16	Left on	Left on	Left on	Left on
23-Apr-16	Weekend excluded	Weekend excluded	Weekend excluded	Weekend excluded
24-Apr-16	Weekend excluded	Weekend excluded	Weekend excluded	Weekend excluded
25-Apr-16	Left on	Left on	Left on	Left on
26-Apr-16	Switched off & on	Switched off & on	Switched off & on	Switched off & on
27-Apr-16	Left on	Left on	Left on	Left on
28-Apr-16	Switched off & on	Switched off & on	Switched off & on	Switched off & on
29-Apr-16	Left on	Left on	Left on	Left on
30-Apr-16	Weekend excluded	Weekend excluded	Weekend excluded	Weekend excluded
01-May-16	Weekend excluded	Weekend excluded	Weekend excluded	Weekend excluded
02-May-16	Left on	Left on	Left on	Left on
03-May-16	Switched off & on	Switched off & on	Switched off & on	Switched off & on
04-May-16	Left on	Left on	Left on	Left on
05-May-16	Switched off & on	Switched off & on	Switched off & on	Switched off & on
06-May-16	Left on	Left on	Left on	Left on
07-May-16	Weekend excluded	Weekend excluded	Weekend excluded	Weekend excluded
08-May-16	Weekend excluded	Weekend excluded	Weekend excluded	Weekend excluded

Date	Matrimandir	Town Hall	SAIIER	Auroville Foundation
09-May-16	Left on	Left on	Left on	Left on
10-May-16	Switched off & on	Switched off & on	Switched off & on	Switched off & on
11-May-16	Left on	Left on	Left on	Left on
12-May-16	Switched off & on	Switched off & on	Switched off & on	Switched off & on
13-May-16	Left on	Left on	Left on	Left on
14-May-16	Weekend excluded	Weekend excluded	Weekend excluded	Weekend excluded
15-May-16	Weekend excluded	Weekend excluded	Weekend excluded	Weekend excluded
16-May-16	Left on	Left on	Left on	Left on
17-May-16	Switched off & on	Switched off & on	Switched off & on	Switched off & on
18-May-16	Left on	Left on	Left on	Left on
19-May-16	Switched off & on	Switched off & on	Switched off & on	Switched off & on
20-May-16	Left on	Left on	Left on	Left on
21-May-16	Weekend excluded	Weekend excluded	Weekend excluded	Weekend excluded
22-May-16	Weekend excluded	Weekend excluded	Weekend excluded	Weekend excluded
23-May-16	Left on	Left on	Left on	Left on
24-May-16	Switched off & on	Switched off & on	Switched off & on	Switched off & on
25-May-16	Left on	Left on	Left on	Left on
26-May-16	- Rescheduled -	- Rescheduled -	- Rescheduled -	- Rescheduled -
27-May-16	Switched off & on	- Rescheduled -	- Rescheduled -	- Rescheduled -
28-May-16	Weekend excluded	Weekend excluded	Weekend excluded	Weekend excluded
29-May-16	Weekend excluded	Weekend excluded	Weekend excluded	Weekend excluded
30-May-16	Left on	Left on	Left on	Left on
31-May-16	Switched off & on	Switched off & on	Switched off & on	Switched off & on

B – MAROMA LT DISTRIBUTION NETWORK

Date	Maroma
01-Oct-16	Weekend excluded
02-Oct-16	Weekend excluded
03-Oct-16	Left on
04-Oct-16	Switched off & on
05-Oct-16	Left on
06-Oct-16	Switched off & on
07-Oct-16	Left on
08-Oct-16	Weekend excluded
09-Oct-16	Weekend excluded
10-Oct-16	Left on
11-Oct-16	Switched off & on
12-Oct-16	Left on
13-Oct-16	Switched off & on
14-Oct-16	Left on
15-Oct-16	Weekend excluded
16-Oct-16	Weekend excluded
17-Oct-16	Left on
18-Oct-16	Switched off & on
19-Oct-16	Left on
20-Oct-16	Switched off & on
21-Oct-16	Left on
22-Oct-16	Weekend excluded
23-Oct-16	Weekend excluded
24-Oct-16	Left on
25-Oct-16	Switched off & on
26-Oct-16	Left on
27-Oct-16	Switched off & on
28-Oct-16	Left on
29-Oct-16	Weekend excluded
30-Oct-16	Weekend excluded
31-Oct-16	Left on

Date	Maroma
01-Nov-16	Switched off & on
02-Nov-16	Left on
03-Nov-16	Switched off & on
04-Nov-16	Left on
05-Nov-16	Weekend excluded
06-Nov-16	Weekend excluded
07-Nov-16	Left on
08-Nov-16	Switched off & on
09-Nov-16	Left on
10-Nov-16	Switched off & on
11-Nov-16	Left on
12-Nov-16	Weekend excluded
13-Nov-16	Weekend excluded
14-Nov-16	Left on
15-Nov-16	Switched off & on
16-Nov-16	Left on
17-Nov-16	Switched off & on
18-Nov-16	Left on
19-Nov-16	Weekend excluded
20-Nov-16	Weekend excluded
21-Nov-16	Left on
22-Nov-16	Switched off & on
23-Nov-16	Left on
24-Nov-16	Switched off & on
25-Nov-16	Left on
26-Nov-16	Weekend excluded
27-Nov-16	Weekend excluded
28-Nov-16	Left on
29-Nov-16	Switched off & on
30-Nov-16	Left on

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